The Assessment of Medical Gloves for In-Situ Applications

Daniel Preece

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Department of Mechanical Engineering

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Abstract

Medical examination gloves are used worldwide and are one of the most common personal protective equipment (PPE) used. The polymers used to develop these gloves undergo rigorous testing to ensure they meet the requirements for use. Primarily, these tests assess the barrier integrity and tensile properties. The effects of placing a membrane over the hand, however, has been shown to be detrimental to the successful performance of tasks carried out by the wearer. The extent of this reduced performance is unknown, but any reduction in tactility and/or dexterity could be disadvantageous to patient care. It could also impact PPE compliance, causing users to remove gloves for certain tasks. As such, this research introduces a range of test methodologies for donning and doffing gloves, as well as assessing how friction is modified with the introduction of contaminants that are encountered when gloves are worn.

In order to effectively assess glove performance, the environments gloves encounter, which have received little attention in previous studies, should be carefully considered and replicated as closely as possible. The aim of this thesis is to investigate the effects of gloves on users when they are used in-situ Test protocols were developed to cover three key performance areas: donning and doffing, glove contamination, and dexterity. Manual performance tests were set up using readily existing dexterity and sensitivity tests (Purdue pegboard and a simulated tactile (bumps) test). To better understand donning and doffing, friction assessments were conducted to assess the tribological interactions between the skin and the inner surface of glove materials, having undergone different treatments. The friction assessments were repeated for interactions between the outer surface of glove materials and objects with textures that replicated typical hand and tool interactions, both in dry and simulated contamination conditions (water, mucus, blood and other bodily fluids).

Three key stages of the donning process were identified (preparation, hand insertion and manipulation), and in all stages, moisture was found to significantly complicate the donning process, as the gloves stuck to the hands more frequently. In wet-hand conditions, polymer coated latex gloves were quicker to don and had lower friction than chlorinated gloves. In addition, nitrile gloves were manufactured specifically for this project, looking at different thicknesses and chlorination treatment strengths. Chlorinating nitrile gloves at 2000ppm appeared to be more beneficial for donning. Doffing was found to be similar regardless of the material, condition, or thickness.

The gloves that produced stiffer tensile material samples were found to reduce friction and reduce the dexterity performance of the glove users. When gloves were contaminated, friction was found to be greatly reduced when compared to the dry condition. This reduction in friction was greater for latex, which decreased the gross dexterity and sensitivity of the user. Smaller reductions in friction were observed overall with nitrile, combined with an improvement in dexterity and sensitivity. A synthetic blood was also developed and validated for the tribological properties to circumvent the need for use of animal blood in future friction assessments.

Knowledge of which physical properties affect which key performance area is fundamental to manufacturers. Optimising the combination of these properties (within other constraints such as cost, constituent availability, and ecological impact) will improve task performance, increasing user satisfaction, and ultimately, PPE compliance and patient safety.

Acknowledgements

My sincere thanks go to Professor Matt Carré and Professor Roger Lewis for their support and feedback over the last four years. Thank you for putting up with my everchanging project design, my dynamic nature, and understanding my approach to this project.

I would also like to thank my industry sponsors at Synthomer, Simon Bassett, Peter Shaw and Paul Brooks, for their continued understand of the changing paths of the project, and feedback on the work conducted. In addition, I extend a great thanks to Thian Hong Ng and Heam Kit Tong in the Group Technical Centre in Malaysia for hosting me, training me in the labs, touring me around manufacturing plants, and helping guide the project with valuable feedback, as well as provision of materials and expert advice. Moreover, a massive thank you to Zhenli Wei, for meticulously reading through this thesis and providing expert feedback.

I would also like to extend an, albeit random, thank you to my secondary school science tutors. Kathryn Casey and Adrian Symonds, you not only sparked my interest in science through your admirable teaching, but enabled, and embraced, my critical thinking nature, which was crucial into leading me to this point. Thank you very much.

It would also be negligent of me if I did not thank the people, who supported me through this Ph.D., mostly by distracting me, or allowing me to distract them. Natalie, Zing, John, Rob, Diyana, Raman, Olivia, and Hamzah, thank you. Without you listening to me grumble about statistics, working on different projects with me, or the full scale distracting conversations about nothing, I do not think I would have made it through some of the tougher days. Included in that is Jamie Booth, who managed to get me what I needed, help with experimental designs, and provided much needed perspectives on the project. Individually, you all made this Ph.D. experience much better than I ever thought it could be, and I will relish the memories, and hopefully there will be many more to come.

And lastly, but *definitely* no means least, I give thanks to my wonderful wife Emily Preece. She has read this thesis, and my work over the years, again and again. Without her support I would not be where I am. The last four years would not have been possible, and I would not have the ambition I have today, without the encouragement from my wife, my in-laws, and my family.

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Abbreviations

The following is a list of encountered abbreviations throughout the thesis:

ATR: Attenuated total reflectance

Cl: Chlorinated

cm: Centimetre

CoF: Coefficient of friction

CR: (poly)chloroprene

DI: Deionised

Eb: Elongation at break

Fb: Force at break

FTIR: Fourier transform infrared spectroscopy

HSE: Health and Safety Executive

K: Stiffness

min: Minutes

ml: Millilitre

mm: Millimetre

mPa-s: Millipascals second

N: Newtons

NBR: Acrylonitrile butadiene rubber

NHS: National Health Service

nm: Nanometres

g: Grams

cm: Centimetre

NRL: Natural rubber latex

PC: Polymer coated

phr: Parts per hundred rubber

ppm: Parts per million

PVC: Polyvinyl chloride

R_a: Roughness average

S_a: Surface roughness average

s: Seconds

SB: Synthetic blood

T: Thickness

t: Film thickness

Ts: Tensile Strength

η: Viscosity

ρ: Density

Glossary of Terms

The following is a list of encountered terms used throughout the thesis:

Adsorbed: Substance chemically adhered to a surface of a material

Contact angle: The angle where a liquid meets a substrate, measured by a Goniometer

Covid-19: Contagious respiratory virus (also known as Sars-CoV-2)

Dexterity: Ability to manipulate objects with the hands

Doffing: The act of removing a glove

Donning: The act of putting on a glove

Glove Material: Specific material used to make the glove

Glove: Entire glove system

Hydrophilic: Attracts water

Hydrophobic: Repels water

Phalangeal: Relating to the finger

Proximal: Closer to the body

Standard Deviation: Spread of data, used when averaging repeat measurements

Standard Error: Error from the mean, used when combining and averaging participant performance data to show confidence in the mean.

Stiffness: A systems (e.g. glove) or materials (e.g. nitrile) resistance to deformation when load is applied

Wettability: Preferences of a liquid to sustain contact with a surface, determined by affinity between the materials

Whole Blood: Blood with all components, and no anti-coagulants added

Declaration

I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not previously been presented for an award at this, or any other, university.

Work published from this thesis can be found in the Appendix (A).

Chapter One: Introduction

1.1 Motivation of research

The purpose of medical examination gloves is to act as a first line of personal protective equipment (PPE) for the hands to protect from contamination. For instance, clinical staff, such as doctors and surgeons are required to don medical gloves to protect themselves and patients from pathogens. Once manufactured, the industry looks very closely at assessing whether these gloves are good enough to act as a barrier. However, there is relatively little research oriented towards how these gloves affect the performance the user. This Ph.D. research is sponsored by Synthomer, a global supplier of aqueous polymers, who supply nitrile glove polymers to leading glove manufacturers (1). Predicted to raise to £6.1 billion in the 2020 global market, up from 7.2% in 2017, the medical glove industry dominates the market in PPE. Driving factors around this increase in market value are the stringent regulations in clinical settings, personal care, sanitation and any situations where contamination of the skin may be an issue (2). The demand for gloves has increased due to the surge in the SARS-CoV-2 (covid-19) pandemic, as gloves are worn more frequently, and changed more often (3). Generally, three types of medical glove exist: examination, surgical, and chemotherapy. The work conducted in this thesis focussed on one type of medical glove, examination, as these are most commonly used. Chemotherapy gloves are thicker, to prevent radiation penetrating rapidly to the skin. Surgical gloves are similar to examination gloves, but they exist in more precise sizing and are said to offer better tactile sensitivity. These are also made more durable, for prolonged periods of use (4, 5). Glove manufacturers and material suppliers (such as Synthomer) are the two industries that are key to the development of medical gloves and share the same goal; to improve user compatibility and performance of medical gloves, whilst maintaining or potentially saving costs. Therefore, the main aim of this work is to understand the effects gloves have on users when they are replicating the conditions they encounter when in use.

Research into the glove materials by these industries focuses on streamlining processes, and the generation of new glove polymers. This has led to the expansion of non-latex polymers, such as nitrile butadiene rubber, popular due to the characteristics being similar to that of natural latex. Furthermore, the increased use of synthetics curtails the likelihood of adverse reactions to the gloves due to rising latex allergies. The market trends now lean more towards these non-latex alternatives, with nitrile being the most common examination glove being developed (2). New techniques and processes facilitate an alteration in the chemistry of the butadiene rubber, allowing different gloves to be created. These gloves are an improvement on the younger generations of nitrile, offering better mechanical properties or different chemical resistant capabilities. However, as these glove materials change, it is unknown if the effects they have on user performance changes. Understanding how the differences in material parameters affect different aspects of glove use will allow Synthomer, and polymer chemists, to develop gloves that can be manufactured for specific purposes (e.g. improved dexterity). It may be worrying to think that what is seen as first line defence PPE, could contribute to a reduction in health care capability, and a rise in misdiagnoses. However, this may be the case (6–9).

Although little work exists looking at the impact of gloves on the performance, the World Health Organisation estimates there is between a 0.005-0.02% chance of having equipment retained after surgery (10). Conversely, studies have stated that the risk is much higher, around 12.5% (11). Most commonly, the equipment is small items such as sponges, scissors, and pins. However, measuring devices, scopes and even instruction manuals have been found in people after surgeries. It is unknown as to how this occurs. It is suggested the hastiness of some surgeries affects the judgement of the surgeon (10). However, surgical work requires tactile exploration in order to identify areas in the body. It is just as possible that same tactile sensation that allows them to feel the body, has failed to allow the identification of foreign objects (6, 7, 12). Although examination gloves are not used in surgeries, this is indicative that problems exist, and in the wider context, examination gloves are more routinely used than surgical gloves. Another example of this is highlighted in a study by Jones, Friend, Dreher, *et al.* (13) who found that of 3225 patients, 510 may have had their prostate cancer missed upon manual exploration. It is not possible to conclude that the gloves are the cause of this, but it is reasonable to assume that the gloves may have dampened sensitivity, possibly leading to misdiagnosis in some of these cases. The underlying theme of both the retained instruments and the missed prostate cancer is that the tactility and dexterity, vital for the tasks, may have been impinged by the use of gloves. Studies have shown gloves affect sensitivity, and in some instances, dexterity is also affected, which could lead to poor patient care (6, 12). In addition, many of these studies do not consider the situations gloves will be used in, and are studied in a dry, uncontaminated condition. The understanding of how these gloves both interact with these contaminants, and how the performance (task, protection, ease of use) is affected, is also not well researched in the literature. Therefore, there is a requirement for assessments that replicate the conditions in which gloves are used, to fully assess the effects of various properties on glove performance.

1.2 Aims of research

The aim of this research is to improve how medical examination gloves can be assessed in a way that replicates their use in working environments, as opposed to previous work where simplistic testing was used to assess the effects of gloves on the user. The understanding gained from these assessments can then inform manufacturers how the use of different glove polymers, and treatments, will affect the performance of tasks carried out when wearing gloves, including the donning and doffing process. The research in this thesis can then be oriented at both filling the gaps in knowledge and making the assessments more applicable to manufacturers, such as Synthomer. In order to do that, the thesis explores the manufacturing of these medical gloves, and the differences present between them. The objectives of this thesis are as follows:

- To review the literature published on the assessment of medical gloves and liaise with industry to understand the assessments being conducted under the standardised testing. There is a requirement to identify unexplored areas in current literature by the way of a paper grading. This allows for identification of how previous research can be made more applicable, to replicate representative working conditions.
- To gain knowledge of where the user issues lie with gloves through the use of questionnaires. In conjunction with this, knowledge of what the gloves are used for will allow a more targeted approach for understand the contaminants gloves encounter when being used. This will be conducted thought the use of surveys to understand the perception amongst common examination glove users.
- Understanding the tribological interactions between gloves and a variety of surfaces is salient, and seldom studied (6). Furthermore, assessing how these tribological interactions are altered by the presence of contaminants, such as blood and powders, are important, as this altered friction could cause issues with equipment being dropped/slipping out of the hands. In addition, it is possible that in medical examinations, where gloves are required, information that is received through the haptic interface could be missed (13). Thus, assessing how contaminants affect glove friction, and ultimately, performance is explored in this thesis using common contaminants (mucus, oil, blood, water, disinfectant, and powder), informed from everyday glove users. This allows for an assessment of the effects contaminated gloves have on friction and the performance parameters of glove users.
- The interaction between gloves and skin has received little attention in the literature. The donnability of gloves is of a great research interest to the manufacturing industry, as

different coatings applied to the inside of gloves are said to produce different results in terms of ease of donning (14–16). Development of methodologies to assess donning and doffing will help investigate how different coating and treatments impact the user experience. In addition, the differences in frictional properties can be highlighted and linked to the physical parameters of the materials. From this, an understanding of the fundamental skin-polymer interactions can be gained, which can inform manufacturers and glove users on glove selection and development.

- The chemistry of medical gloves is well understood in the glove industry, allowing the patented formations of nitrile to be developed and used for film formation by the raw material manufacturers. Knowledge of how these chemical changes affect the glove performance in terms of tensile properties and puncture resistance are studied and recognised in the industry. However, the linking of the changes in chemistry, and ultimately physical changes, to the performance has had little exploration, and requires investigation. By using gloves of the same core materials, but with different additives or treatments, the effects of gloves on donning, sensitivity, dexterity and friction can be understood. In addition, the thesis focuses on the replicability of these tests, and putting them into industry as an assessment method. This understanding can then inform manufacturers of which physical properties of the gloves affect the end performance of glove users.

1.3 Novelty and Impact

The research conducted in this thesis offers new methodologies for assessing glove performance from an ergonomic and tribological viewpoint. By obtaining information from glove users about their perceived issues with gloves, the research was tailored to replicate the conditions gloves encounter when in use. The applicability of tests to the conditions they are used in is lacking in the literature, rendering some of the work obsolete, and incomparable. Thus, the assessments conducted in this thesis, draws focus on the needs of the users, in order to make the research relevant to the everyday problems, and aims to be suitable for adoption by industry. In some cases, the assessments may not induce repeatable tests in industries (such as the donning of gloves), without further refinement, but the research can give insight into how the gloves affect user performance. The research conducted throughout this thesis has led to multiple research outputs including publications (Appendix: Section A) and several industry presentations, including to glove material manufacturers, and glove manufacturing plants in Malaysia. The originality of the thesis takes a fresh approach on the work industry normally conducts, linking their mechanical tests, and chemical development, to the impact gloves have on users in-situ. Finer details on the novelty and impact can be found in Chapter 10, Section 10.1.

1.4 Structure of thesis

This thesis is organised into ten chapters that address the key aspects of the research. These are also set out in Figure 1.1.

Chapter 1 gives an overview of the issues which drive the need for the research and the novelty and impact of the work conducted. In this chapter, the aims and objectives of the thesis are also described.

Chapter 2 provides insight into how gloves are manufactured, processed, and assessed. The review also provides an evaluation of the present understanding of how medical examination gloves have been assessed in the literature, and the need to incorporate the conditions gloves are used in, to fully understand the tribological properties of gloves.

Chapter 3 investigates where research should be focused, by asking participants who use medical examination gloves to provide answers on how gloves affect their performances, and what contaminants they are likely to encounter in their profession.

Chapter 4 focuses on the inner side of the gloves, which is the 'donning side'. The effects of different glove materials and different finishing coatings/treatments are assessed for their donnability and doffability, along with assessments of how the frictional properties change between the glove coatings and treatments.

Chapter 5 closely follows the protocols developed in Chapter 4, looking at the donning of medical examination gloves. However, this chapter looks gloves that have been formed ad-hoc, to assess the frictional properties of different thicknesses and chlorination treatments. The chapter also aims to link the performance to the mechanical and chemical nature of the gloves.

Chapter 6 looks into the differences in the physical and chemical properties of commercially available gloves and evaluates the frictional performance in relation to dexterity performance. Also discussed in this chapter are issues around fit, and how differences in manufacturing processes, may affect the glove users' experiences.

Chapter 7 explores the frictional interactions with different surfaces and contaminants, which are found throughout the clinical sector. Furthermore, analysis of the chemical changes that may occur in gloves is also explored.

Chapter 8 investigates how performance parameters, such as dexterity and sensitivity, is affected when medical examination gloves are contaminated with mucus.

Chapter 9 concentrates on the development of synthetic blood surrogates for use in future studies. Validation of the bloods is carried out by tribological assessments with whole ovine blood.

Chapter 10 concludes the work by summarising the key findings from the previous chapters, with industry recommendations, and discussing the future work needed.

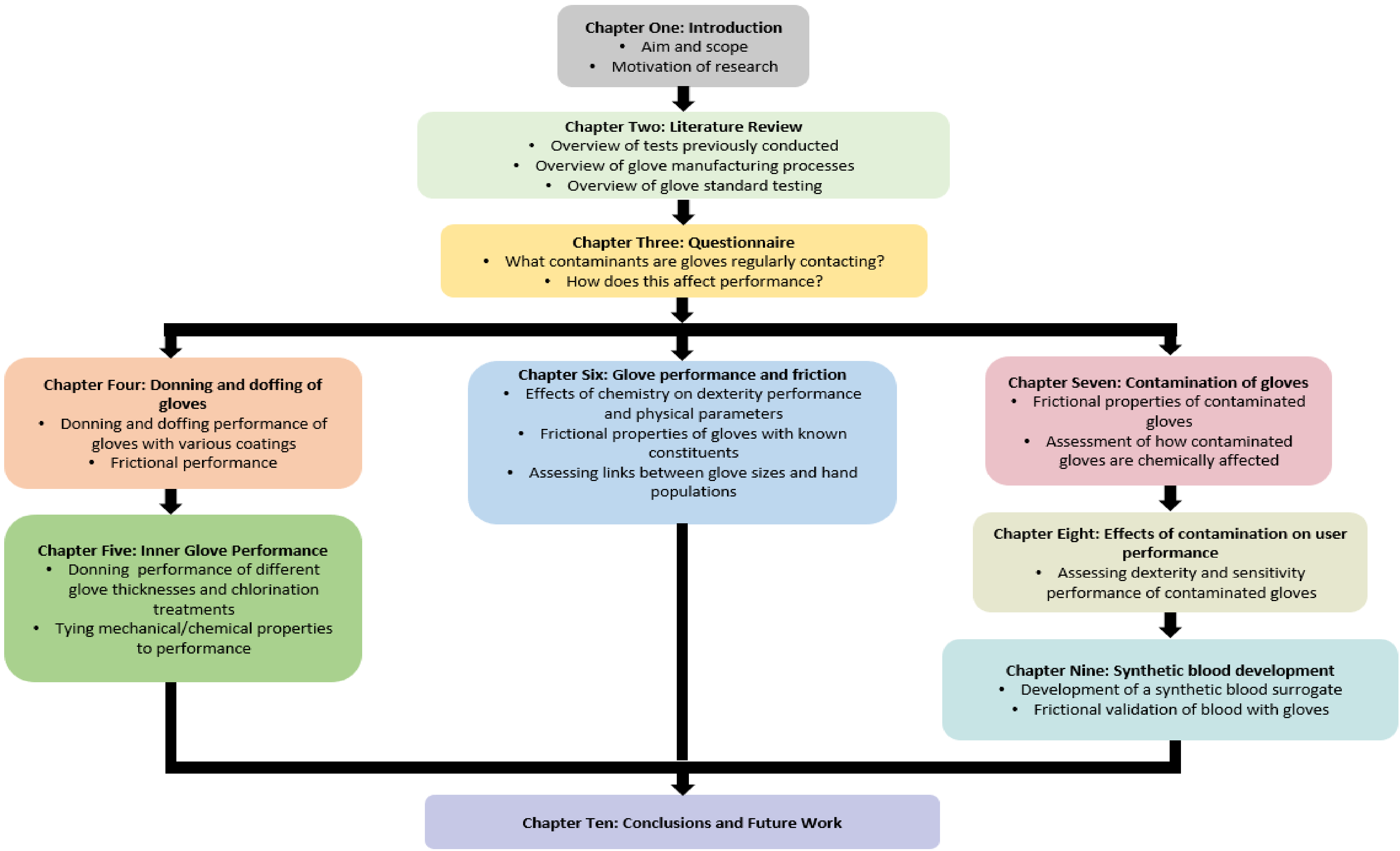


Figure 1.1. Structure of thesis

Chapter Two: Literature review

2.1 Introduction

The safety performance of medical examination gloves is relatively undisputed. However, it has yet to be determined as to how gloves should be assessed for quality of purpose. Does placing a membrane over the hand have such an effect on performance that a medical professional cannot perform tasks correctly? This review aims to bring together the knowledge available on how medical glove performance has been assessed within the literature. Firstly, focusing on the varied materials of gloves before discussing how gloves have been assessed in previous studies. The advantages and limitations of such assessments will be discussed, and suggestions will be made on improvements if and where applicable. As the review is focusing on glove use in-situ, studies focusing on sensitivity, dexterity, friction, grip, and performance perception will be evaluated.

2.2 Medical glove use

The purpose of medical gloves is to prevent the hands from becoming contaminated, or to avoid contaminating a surface or patient. There is a general consensus in the literature, and in guidelines, as to when gloves should be donned. The use of gloves in a clinical setting is based on a risk assessment of the overall task. This risk assessment takes into account the chances of contact with bodily fluids such as blood; broken skin; excretions; secretions and hazardous chemicals/drugs (17–19). It is generally accepted that gloves are not necessary when administering vaccine injections unless broken skin is present on either parties or there is anticipated exposure to bodily fluids (20). The National Health Service (NHS) provides a standard operating procedure for all glove use, although this differs slightly between trusts. For example, the Lincolnshire trust avoids the use of natural rubber latex gloves whereas the Hampshire trust requires participation by users in a skin monitoring programme (21, 22).

Expert opinion appears to be at the forefront of the decision as to when to wear either surgical gloves or examination gloves to carry out minor surgeries. Medical examination gloves are recommended for oral care; cannulation, blood exposure, rectal/vaginal examinations and many minor procedures (21–24). It could be argued that, as minor surgery is still surgery, surgical gloves should be donned. Nevertheless, outside of an operating theatre, medical examination gloves are the primary gloves used. Figure 2.1 shows a list of procedures carried out using medical examination gloves in the NHS (23).

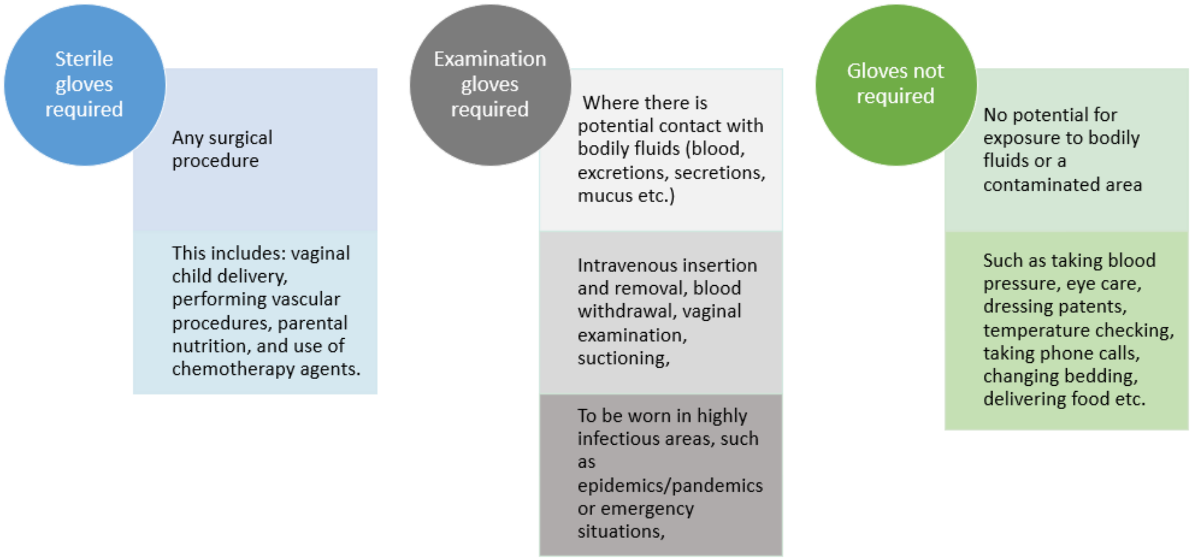


Figure 2.1. Glove use procedure policy. Recreated from NHS guidelines (23).

Nursing Times Magazine published an article on what gloves to wear and when, stating that the NHS uses only sterile examination gloves for aseptic procedures and minor surgery (25). Many studies have been carried out assessing whether gloves used should be sterile or non-sterile (26–29), all of which conclude that gloves do not need to be sterile in minor procedures as the risk of infection is low and contamination of gloves is rare. However, it is recommended for sebaceous cyst excisions that sterile examination gloves be worn. With the outbreak of covid-19 leading to a pandemic, the NHS recommends gloves are worn by all clinical staff, for any contact with a patient (30, 31).

2.3 Glove Materials and market trends

The properties of gloves are dependent upon the raw manufacturing materials, manufacturing processes followed, and the chemical treatment gloves receive. Natural rubbers are commonly used, the most prominent being natural rubber latex (NRL), a substance found in the bark of *Hevea* trees (32). NRL is known as a homopolymer, a repeating unit of the single monomer 1,4-cis polyisoprene as shown in Figure 2.2 (33). By nature, the material is a highly deformable elastomer, allowing easy conformation to the shape of the hand (14).

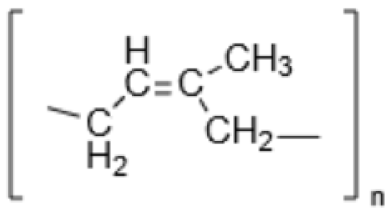


Figure 2.2. Structure of the polyisoprene monomer making up the NRL.

The Center for Disease Control (CDC) estimates that up to 6% of the worldwide population has a latex allergy (34). Furthermore, the increasing incidence in NRL allergies means that alternative glove materials must be used where appropriate. Other glove materials include nitrile butadiene rubber (NBR), polyvinyl chloride (PVC) and polychloroprene (CR) (35, 36). The most common alternative material to NRL is NBR, synthetically created using a copolymer of acrylonitrile and butadiene (Figure 2.2). However, the elastic loading response of NBR means that the conformability to the hand is perceived to be inferior than that of NRL (7). The stiffness of NBR gloves is an issue for some, as they report it hinders their ability to carry out tasks (7, 36). Different grades and generations of NBR have been developed over time to accommodate various properties and manufacturing processes. The most common is the carboxylated NBR (XNBR). XNBR gloves have a carboxyl group (COO-) introduced from acrylic acid, which is added to the acrylonitrile and butadiene (Figure 2.3). This allows for ionic cross-linking with zinc during glove formation, allowing for more improved physical properties such as tensile strength and lower stiffness (37).

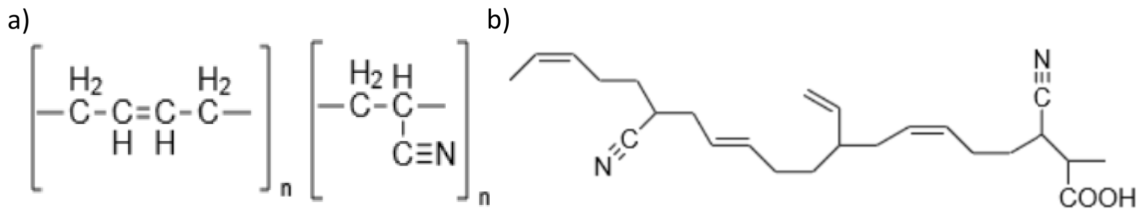


Figure 2.3 a-b. a) Structure of the butadiene (left) and acrylonitrile (right) monomers which form the copolymer nitrile butadiene rubber (NBR). b) Most commonly used for glove manufacturing is XNBR, which is formed upon the addition of acrylic acid to the monomers shown in a (37).

Due to the prevalence of rising latex allergies, shifts have been evident in the market with regards to medical glove use. NBR can be manufactured to a thinner gauge, thus trends over time have seen gloves decrease in thickness from a standard of 0.1 mm to around 0.05 mm (38). This uses less material, which has reported benefits for the end users, such as a greater tactile sensitivity, allowing a greater sense of feeling (39–41). In addition to this, thinner gloves mean cheaper costs for manufacturers, as less material is used. The manufacture of NRL gloves, requires the latex to be sourced, tapped, and transported. This is added labour and time costs for manufacturing plants. As NBR, CR and PVC are synthetic, there is no need for any additional labour costs to obtain natural ingredients (39). The relaxation of the EN standard for force at break (9 N to 6 N) has also allowed manufacturers to make NBR gloves of a thinner gauge (38, 42). However, challenges are presented with this for manufacturers, finding materials that meet the specification of a break force of 6 N at

0.05 mm proves difficult. This has led to the development of multiple generations of NBR materials over the years, each with different chemical and mechanical properties (38, 43).

2.4 Glove Manufacturing

The final glove product performance is influenced by many factors in the glove manufacturing process, including difference in chemicals used at each stage, raw materials and the differences in manufacturing methods (14, 38). In the first instance, the raw glove materials need to be compounded with other materials to help control the glove development process. These compounded materials contain not only the core glove material (such as NRL), but a variety of accelerators, activators, cross linkers, vulcanising agents and anti-ageing additives are also added, which will affect the overall end product (14). With the rising cost of materials, gloves are sometimes bulked out with filler materials to extend their yield. NRL liquid contains a mixture of the rubber suspension, sugars, resins and proteins, whereas synthetics (NBR, PVC, CR) requires polymer emulsification to create the raw material (38). This takes place by mechanical shearing of the monomers making up the NBR polymer compound. The process allows for particle size, structure, and shape to be controlled. The particle size of the synthetic latex matrices (NBR) tends to be between 0.1-1.0 µm, whereas the NRL tends to have larger particle sizes around 0.3-2.0 µm (14, 44, 45).

2.4.1 Manufacturing Process

Porcelain formers (moulds) are used to form the gloves following the simplified flow chart shown in Figure 2.4. The formers must be clean and free from contamination, as small imperfections, dust, glove residues can cause defects in the product formed (46). A clean former is dipped into a coagulant. The coagulant acts to destabilise the compounded NRL/NBR material and adhere the material to the former, creating the glove film. Thus, the amount of coagulant present on the former controls the thickness of the glove material. The longer the former is held in the coagulant (dwell time), the thicker the glove will be. Most commonly, the coagulant is calcium nitrate, but other coagulants can be used (14). The coagulant covered former is then dried in an oven before being dipped into the compounded glove material. The deposited material will take on the shape of the former, developing the glove, as shown in Figure 2.5. This is then leached by placing the former in hot water to remove residual surfactant from the wet NBR film. Where NRL gloves are used, this leaching process has also shown to remove some of the proteins which cause allergies. The leached product then undergoes vulcanisation in an oven in order to achieve the final physical properties and dry out the material (14, 19, 38).

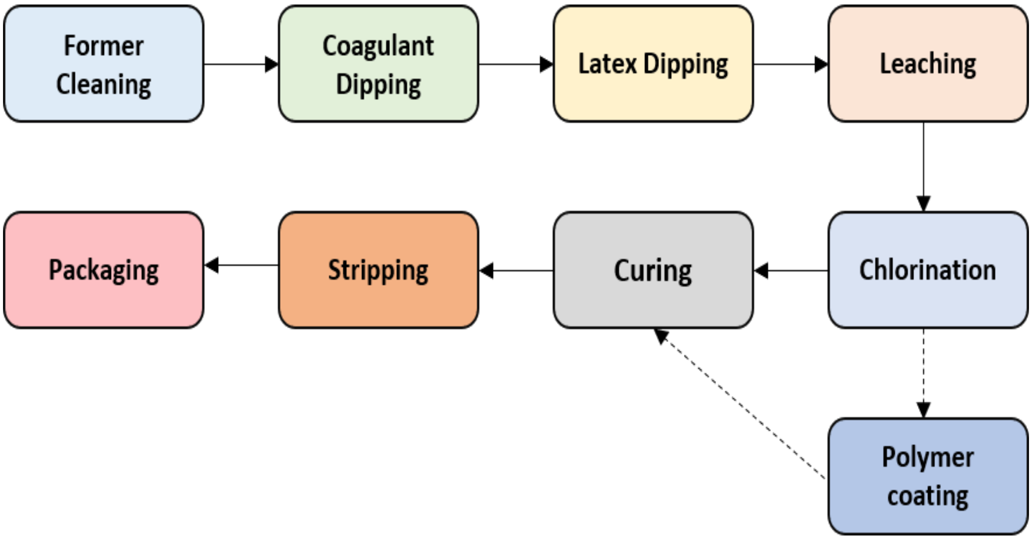


Figure 2.4. Glove manufacturing process

Figure 2.5. Glove formed on porcelain mould.

2.4.2 Post-dip processing

The final product will need treatment to reduce the surface tackiness of the material. This tackiness reportedly makes the gloves harder to don and allows gloves to stick to each other in the packaging, causing issues when trying to remove from the boxes (47). It is important to note, that whilst on the former, the glove surface exposed to the atmosphere becomes in the inner surface of the glove. This form of manufacturing process is known as 'on-line' and requires no human intervention to carry out any part of the process (48). Until 2000, powder (such as starch) was used to coat the donning surface.

However, due to the rise in the incidents of latex allergies, there have been concerns over the proteins in NRL being made airborne upon the removal of the glove after the powder has interacted with the latex proteins (34, 49). Consequently, in 2010 the Health and Safety Executive (in the UK) released guidelines stating that NRL gloves must be free of powder, prompting the NHS to stop purchasing powdered NRL gloves (50).

Chlorination

Since the halt on using powders on gloves came into effect, chlorination has become the most utilised method of treating gloves.
There are three ways to induce glove chlorination, which are as follows:

- Chlorine gas can be dissolved into water and gloves subsequently held into the water
- Exposure of gloves to an aqueous solution of organic chlorine
- Acidification of an aqueous solution of sodium hypochlorite with hydrochloric acid, and sodium thiosulphate neutralisation, which the gloves are then dipped into (51, 52)

For this research, the acidification process was used. Chlorine (Cl) is released via hydrolysis of the Sodium hypochlorite (NaClO) with water (H_2O) to release hypochlorous acid (HClO) (53):

$$NaClO + H_2O \Leftrightarrow Na^{+} + HClO + OH$$

The hypochlorous acid then further dissociates to form chlorine (Cl_2):

$$HClO + H_3O^{+} + Cl^{-} \Leftrightarrow Cl_2 + 2H_2O$$

In the on-line chlorination procedure, the gloves are still on the former, and are exposed to a chlorine solution, usually in a rotating drum (14, 47). This is then neutralised with water and then dried to form the final product. Other methods of chlorination exist, including allowing the chlorination of both the inside and outside of the gloves (depending on the chlorine strength). However, the on-line method is most common (16, 38, 51). In the chlorination process, the polyisoprene double bonds in the latex polymer are susceptible to the addition of chlorine (14, 54). This allows chlorine onto the surface, acting as an accelerated ageing, which removes the surface tack and stiffens the material. As this is an age accelerating process, the chlorination stage needs to be tightly controlled, as this severely affects the shelf-life of the finished product. Where NRL has been used, over-chlorination can be identified by the discolouration on the glove (16, 55). Double-dip chlorination can also be used, whereby the gloves are chlorinated twice to further reduce the surface tack. Gloves that are not chlorinated twice have better grip properties for the user, but stick to each other in the box, causing issues regarding dispensing (14, 38).

Surface coating

As an extra step to the chlorination process, the glove films can also be treated by a chemical coating. Coating with polymers, such as hydrogel, a hydrophilic acrylic polymer which absorbs moisture, gives the glove surfaces a smoother finish (56, 57). This is said to improve the donnability of the glove material. There are two methods whereby polymer coatings would work. Coating with a hydrogel will allow the absorption of water (hydrophilic), causing the inner surface to be slippery, allowing a smoother frictional interaction between the skin and the polymer. If coated with a hydrophobic coating, then the water will be repelled, separating the skin from the polymer and reducing contact (16). This allows the moisture to effectively act as a lubricant. Yip and Cacoli (14) hypothesise that these surface treatments are good for donning, as they provide a topography which consists of hard spherical particles, which are fixed into the soft polymer matrix. This allows a smooth interaction for the skin, as it rolls over in a 'ball-bearing' fashion, reducing surface contact area. The application of these coatings is not well discussed in the literature, due to them being patented technologies. Coatings can be applied on-line before the final drying stage. Priming the wet gel before dipping into the coating can aid the adhesion of the coating. The gloves that are removed from the formers at the end of the process can also be treated by washing the gloves in the desired treatment polymer. This method results in coating both the inside and the outside of the glove, which may affect properties such as grip, as discussed with chlorination. Other polymers such as polyurethane can also be used, and new polymers are being developed such as the anti-microbial chlorhexidine-gluconate coating (58).

2.5 Glove Standards

After manufacturing, the gloves are tested to check if they comply with appropriate standards. Gloves must conform to either the American Society for Testing and Materials (ASTM) or European Norm (EN) standards, which contain slightly different requirements of the films, as shown in Table 2.1. In order to be used in the United Kingdom, gloves must conform to the EN455 standard (59, 60). This standard covers the testing of the gloves for integrity, strength, shelf life and carries the CE mark. Gloves must also comply with EN 374, which describe the properties required by gloves to protect from chemicals and micro-organisms (61, 62). To test the gloves, every batch formed will have a percentage removed and tested for pinhole leaks, chemical permeation, visual defects and tested for their mechanical properties. Mechanical properties include testing for the force at break, tensile strength, and the elongation. The key differences between the EN and ASTM standards are the width of the material sample cut for testing, and the tolerances of these tests (38). These tested gloves must fall into an Acceptable Quality Level (AQL), which for the EN is 1.5%, which meets the requirements of the Medical

Device Directive. The AQL level is calculated as a percentage of the batch of gloves that contains any defects and this must not be exceeded (60).

Table 2.1. Standards for medical examination glove testing (38) showing force at break (Fb), elongation (Eb) and tensile strength (Ts).

Standard	**Sample width (mm)**	**Thickness (mm)**	**Before Aging**			**After Aging**		
			Fb (N)	**Eb (%)**	**Ts (MPa)**	**Fb (N)**	**Eb (%)**	**Ts (MPa)**
EN	3		≥6.0			≥6.0		
ASTM	6	≥0.05		≥500	≥14.0		≥400	≥14

2.6 Medical glove assessments

Although a lot of testing is present to ensure the glove is acting as an integral barrier to the hands, there is little testing in industry with regards to how these gloves interact with the user, and in turn, their end performance. It can be argued that the glove assessments and standards should also be focusing more on the user compatibility, rather than just the protection properties of the gloves. Very few areas of literature aim to seek out how medical gloves can be assessed to fully evaluate the extent at which placing a barrier between the fingers and the patient or tools in a medical setting can, for instance, affect tactile and haptic feedback.

2.6.1 Tactile Sensitivity

Tactile sensitivity is defined as the ability to extract information from a foreign object to determine the texture, shape, size and possibly orientation via manual exploration (63). To facilitate the tactile sensitivity through the glove, thinner gauges have been created. However, questions concerning the rupture rate and durability of these thinner gloves are being raised (64, 65). The most common method of assessing tactile sensitivity is the use of the monofilament tests (Figure 2.6) (12). In this test, the subject is blinded, and a microfilament is pressed onto a part of the hand. Once the filament buckles, the examiner ceases pressure application, and the participant confirms if contact has been felt. The filaments vary in diameter and are identified by manufacturer assigned values ranging from 1.65-6.65 (66). The limit of detection is the smallest diameter that can be sensed by the participant. A major limitation of this test is that the thicker filaments buckle at higher loads. Thus, the pressure at the filament contact will differ between the varying degrees of thickness, as more force is required to make the thicker material buckle. Also, as the filament buckles, the contact area of the thinner filaments are likely to increase, as the nylon bends and presses against the skin, which may lead to a false positive identification.

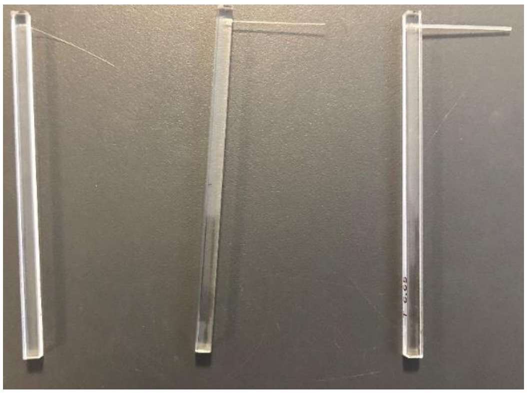


Figure 2.6. Monofilament test showing a range (2.83, 5.07 and 6.10 gauge) of nylon thread thicknesses.

The literature regarding these tests is conflicting. In the monofilament tests, Park, Davare, Falla, *et al.* (63), Novak, Megan, Patterson, *et al.* (67), Tiefenthaler, Gimpl, Wechselberger, *et al.* (68), Bucknor, Karhikesalingam, Markar, *et al.* (69), Mylon, Lewis, Carré *et al.* (70) Che and Ge (71) and Thompson and Lambert (72) state that tactility is reduced whilst using gloves when compared to the bare hand. However, Shih, Vasarhelyi, Dubrowski, *et al.* (73), Nelson and Mital (74) and Johnson, Smith, Duncan *et al.* (75), show that no change in sensitivity is present when donning medical gloves. When comparing glove materials, Kopka, Crawford, and Broome (41) found that there was no difference in sensitivity between NRL and 'NRL-free' gloves. It must be noted, that between these studies, many variations are present in the methodology. Some studies use higher thicknesses of monofilaments to assess sensitivity and different glove materials are used throughout.

Another common method of assessing tactile sensitivity is the use of the two-point discrimination test (Figure 2.7). In this test, two prongs are placed on the skin at varying spacing of 1 -25 mm, with the aim of identifying at what distance the two prongs feel like one (76). The prongs are attached to a disk (10 cm diameter) which allows for easy changing between different sizes. Fry, Harris, Kohnke, *et al.* (77) showed that gloves do not hinder the identification of two distinct points. However, other studies investigating this found that gloves can reduce the discrimination of two points (67–69, 72, 73, 78, 79). Again, this test has limitations, given that there is no limit on how much pressure is put onto the surface by the subject and the glove material can spread out the pressure across the finger.

It has also been noted by Lundborg and Rosén (80) that it can be tempting for examiners to apply enough pressure to evoke a result, introducing bias into these tests and producing inaccurate results. Whilst Fry *et al.* (77) stated that they did not find any differences in 2-point discrimination tactility between gloves and no gloves, they looked at ulnar and radial surface testing. The radial nerve is less likely to serve purpose in clinical situations, as the back of the thumb or hand is less likely to be used (81), which draws questions on the effect gloves have on tactility.

Figure 2.7. Two-point discrimination touch test. Point spacing numbers correspond to mm of the two distinct points.

Other commonly occurring tests in the literature involve the use of roughness discrimination. These tests require participants to identify varying bump sizes or roughness/patterns (63, 70, 82–86). Of these, only two studies found that detection rates declined when gloves were worn (63, 86). Sandpaper (and different paper grits) has also been used as a means of measuring discrimination. Mylon, Buckley-Johnstone, Lewis, *et al.* (87) showed that subjects could perceive roughness differences when moving their gloved fingers across sandpaper, but not when statically pressing. Palpation or surface anomaly detection with patients would require interaction with skin and tissue that is much more viscoelastic and pliable than the materials used in these studies. Thus, it would be imprudent to say that gloves have no effect on the ability to discriminate surface anomalies on or within the body by these test methods. More advanced assessment methods have been produced, such as the Simulated Medical Examination Tactile Tests (SMETT) developed by Mylon, Lewis, Carré, *et al.* (88). In the 'bumps' SMETT test, 100-600µm pimples were 3D printed on a soft rubber-like sheet which was fixed onto a board. Participants were asked to run their fingers across the sheet to see if any pimples were identifiable. The 'Princess and the Pea' SMETT test required participants to identify pegs of varying heights (2.5-14.5mm) which were submerged in silicone. This was based on the Hans Christian Anderson tale, titled by the same name, whereby the royalty of a woman is identified by her ability to feel a pea placed under her mattress (89). A similar test was carried out by Gnaneswaran, Mudunuri, and Bishu (86) which utilized 1.25cm dried glue spots covered by sponge. Although the SMETT tests in Mylon *et al.* (88) do appear to be a valid means of in-situ glove assessment, several areas with room for improvement exist in the methodology and design. It was found that the silicone became stiffer over time, making it harder to identify the pegs. Participants also varied placing their fingers flat or perpendicular to the test beds, which could produce different results due to the dispersion of mechanoreceptors. This could provide differing results between people and between the gloving conditions. Although the bumps and roughness discrimination tests are a good measure of identifying tactility loss, it could be argued that the use of more appropriate surfaces that replicate the body and environmental conditions would lead to more accurate results in a clinical context.

An inability to detect a pulse is the most common reported reason for removing or not donning gloves. A study by Mylon, Lewis, Carré, *et al.* (8) considered the effects of gloves on pulse detection using a design whereby water was pumped through one of five tubes under a layer of neoprene sponge using a peristaltic pump. They found significant differences in ability to feel the 'pulse' in gloved and ungloved conditions. The authors note that this cannot accurately simulate a pulse test due to the pump limitations on the speed and pressure. Also, there was the potential for bias due to the inability to vary the pulse location. Using a pump that will allow the same pressure and speed of blood would be more simulative of in-situ glove use. A more quantifiable way of assessing tactility differences is by using vibrations. Carré, Tan, Mylon, *et al.* (90) used a vibrating platform to measure the sensitivity difference of fingers when a NRL glove was donned. The glove was found to reduce tactility when compared to the no-gloves condition. However, only one participant was used for this. Overall, studies regarding tactile sensation show that gloves have an adverse effect on ability to feel. However, the extent to which this becomes a detriment remains unknown. Many of these tests aim to quantify tactility loss, but results differ between studies, possibly due to the different methodology used. To quantify tactility loss, further studies looking at how the gloves dampen vibration, like in Carré *et al.* (90), could prove vital for future work. Some of the studies discussed here were conducted prior to the banning of powder coated NRL, thus the results may not be applicable to gloves used today due to the differences in manufacturing. Gnaneswaran *et al.* (86) stated that powdered NRL gloves are better because they have ideal properties, such conforming to the hands better. There is a chance that this powder could affect the frictional properties of gloves in any of dynamic tactility tests, which may give different results. Many of the studies cited regarding sensitivity are vague in terminology, describing the gloves tested as 'thick' or 'thin' without giving any measurements. Due to the issues arising with these assessments, it is unknown as to how much medical gloves affect the tactile sensitivity of a user, but it is clear they are having a negative effect.

When comparing glove thickness, studies have found that the thinner gloves provide more sensitivity (41, 78). Surgical gloves are often marketed as offering better ‘tactile sensitivity’. However, studies looking at the difference between medical examination and surgical gloves have found no measurable difference in sensitivity (68). Table 2.2 shows a breakdown of the available literature regarding tactile tests where the use of gloves has been compared to the bare hand condition.

Table 2.2. Studies relating to the effect gloves have on tactile sensitivity. Reduced sensitivity is defined as a reduction in ability to discriminate or identify sensations.

Study	**No of Participants**	**Materials**	**Test**	**Results**
Brunick, Burns, Gross, *et al.* (84)	29	NRL and Vinyl	Roughness discrimination	No significant difference observed
Nelson and Mital (74)	20	NRL	Roughness discrimination, needlestick	No significant difference observed
Klatzy and Lederman (85)	12	NRL	Roughness discrimination	Similar results between bare finger and gloved finger
Mylon *et al.* (87)	30	NRL and NBR	Roughness discrimination	Reduced roughness perception
Phillips, Birch, and Ribbans (79)	20	NRL	Two-point discrimination Roughness discrimination	No significant difference observed
Thompson and Lambert (72)	20 and 30	NRL	Two-point discrimination Monofilament Vein location	Tactile sensitivity reduced with gloves
Han, Kim, Moon, *et al.* (78)	40	NRL	Two-point discrimination	Tactile sensitivity reduced with glove
Fry *et al.* (77)	53	Not Stated	Two-point discrimination	No significant difference observed

Shih *et al.* (73)	10	NRL	Two-point discrimination and monofilament	No significant difference observed
Tiefenthaler *et al.* (68)	20	NRL	Two-point discrimination and monofilament	Tactile sensitivity reduced with gloves
Bucknor *et al.* (69)	52	Not Stated*	Two-point discrimination and monofilament	Tactile sensitivity reduced with gloves
Johnson *et al.* (75)	42	NRL and NBR	Monofilament	No significant difference observed between gloves
Mylon *et al.* (70)	18	NRL and Vinyl	Monofilament	Tactile sensitivity reduced with gloves
Park *et al.* (63)	12	NRL	Bump discrimination	Tactile sensitivity reduced with gloves
Mylon *et al.* (8)	19	NRL and NBR	Pulse location simulation	Tactile sensitivity reduced with gloves
Mylon *et al.* (88)	39 and 34	NRL and NBR	Simulated Medical Examination Tactile Tests (SMETT)	Tactile sensitivity reduced with glove
Carré *et al.* (90)	1	NRL	Vibration sensitivity	Sensitivity reduced with glove

*Presumed to be NRL as the methodology states the participants were asked about NRL allergies.

2.6.2 Dexterity

Dexterity is defined as the ability to carry out tasks using motor skill, moving the hands, fingers and arms. The conformity of bending of the hands and fingers, material folding, and thickness are the main areas were gloves affect dexterity (9). Together these can impact the ability of users to carry out tasks and manipulate objects with fine skill. Numerous dexterity tests have been developed comparing medical glove material performance. Widely used in these studies, are pegboard tests, such as the Purdue Pegboard (Figure 2.8) and the Crawford Small Parts Dexterity Test (CSPDT) (Figure 2.9). Tiffin and Asher (91) produced the Purdue Pegboard test, which is designed to assess gross dexterity by measuring how many pegs can be placed into the board in a set time using both hands and each hand separately. Washers can also be placed on the pegs in the test to allow further, finer assessments. The CSPDT test requires the placement of the pins with the use of tweezers, assessing finer dexterity. The results generally show that dexterity is only significantly affected when thicker or double gloves are worn (31, 37, 40–42, 52, 59–65). Although little difference is observed between gloves, vinyl showed more of a decrease in dexterity when compared to barehanded, whilst NRL shows a minimal decrease. Drabek, Boucek, Buffington, *et al.* (97) demonstrated that vinyl gloves do not affect performance when using a grooved pegboard test (similar to the Purdue Pegboard), regardless of the size of the glove used. However, the study did find that the time taken to remove the pegs from the board was significantly increased when best-fit gloves were worn. Moore, Solipuram, Riley, *et al.* (92), Pourmoghami (94) and Drabek, Boucek, Buffington, *et al.* (99), however, found that dexterity was decreased in the Purdue pegboard test with NRL when the wrong sized glove was worn. Francis, Hanna, Cresswell, *et al.* (100) and Hamstra and Dubrowksi (101) demonstrated the varied skill of professionals is a factor in these assessments. They found students had impaired dexterity and dropped more pins than experienced surgeons in the pegboard tests. This would suggest that in order to accurately interpret results of pegboard tests, recruited participants should all be at the same level of experience. This is an important factor that should be considered in all tests of this manner.

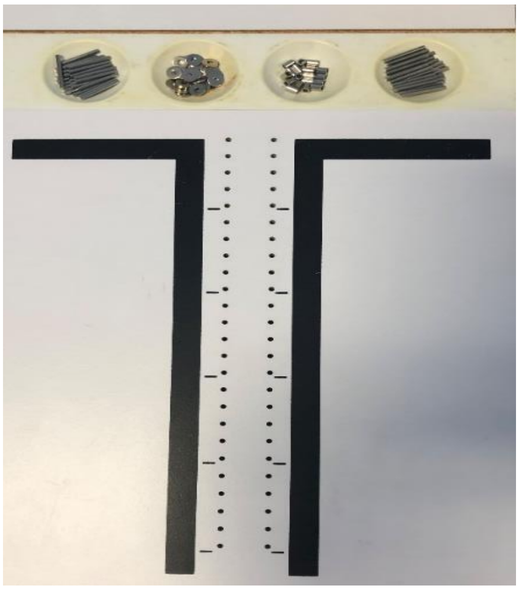


Figure 2.8. Purdue pegboard (46 × 30 cm).

Figure 2.9. Crawford small parts dexterity test (24 × 23 cm).

Gauvin *et al.* (102) states that these dexterity tests are of a good enough sensitivity to measure performance and discriminate between gloves. However, numerous issues exist when using these tests to assess the effects of gloves. The primary issue is that the frictional properties of each person's hand are different. Thus, in the 'no gloves' variable, results could be different due to the variation of skin friction, sweat and oils present naturally on the fingers as well as contaminants (such as food residue). No mention of washing the pegs or hands is present in any of the literature, which would standardise this test and reduce contamination. Many of these studies include the NHS first choice gloves: NBR and NRL as well as gloves that are not commonly used such as butyl and vinyl (20). Nelson and Mital (74) and Gnaneswaran *et al.* (86) investigated the effect of NRL thickness on dexterity by having subjects cut paper along lines using scissors and found that a glove thickness of 0.83 mm did not have an adverse effect on dexterity during the task. Studies oriented at more specific clinical tasks, look at the effect of gloves on suturing and syringing (8, 86). These studies also did not observe any significant effect on dexterity between glove materials. The tasks and protocols in most of these studies are very similar throughout and reveal very little to no impact on dexterity when any of the gloves are donned. This would suggest that either the gloves are not having any effect on dexterity or that the tests are not of a good enough sensitivity to pick up the differences. However, dexterity is reported to be affected when thicker gloves are donned. More novel tests need to be designed to simulate the tasks encountered when gloves are worn. Work has already been carried out in this area (syringing and suturing (8, 86)), but more studies are needed to create a test that produces repeatable, reliable results, and provide enough discrimination to highlight differences between the effects of dexterity with different gloves. Table 2.3 shows a breakdown of available tests within the literature investigating how medical gloves affect dexterity against the bare hand.

Table 2.3: Studies relating to the effect gloves have on the dexterity. Reduced dexterity defined as a reduction in time taken to carry out tasks/quality of task.

Study	**No of Participants**	**Materials**	**Test**	**Results**
Nelson and Mital (74)	20	NRL	Paper Cutting	No effect on dexterity
Mylon *et al.* (8)	19	NRL and NBR	Suturing	No effect on dexterity
Moore *et al.* (92)	27	NRL	Purdue Pegboard	No effect on dexterity, although dexterity reduced if smaller or larger gloves used
Sawyer and Bennet (95)	24	NRL and NBR	Purdue Pegboard	NBR gloves reduced dexterity
Drabek *et al*. (99)	20	NRL	Purdue Pegboard	No effect on dexterity, although dexterity reduced if smaller or larger gloves used
Fry *et al.* (77)	53	Not Stated	Purdue Pegboard	No effect on dexterity
Park *et al*. (63)	12	NRL	Purdue Pegboard	Gloves reduced dexterity
Allahyari, Kahnehshenas, and Khalkhali (98)	30	NRL and NBR	Purdue Pegboard	No effect on dexterity

Pourmoghani (94)	10	NRL	Purdue Pegboard and O'Connor	No effect on dexterity, although dexterity reduced if smaller or larger gloves used
Berger, Krul, and Daanen (96)	30	NBR	Purdue Pegboard and O'Connor	Gloves reduced dexterity
Johnson *et al.* (75)	42	NRL and NBR	Purdue Pegboard and CSPDT	Manual dexterity reduced when thicker gloves worn
Mylon *et al.* (70)	18	NRL and Vinyl	Purdue Pegboard and CSPDT	Gloves reduced dexterity in the Pegboard test but not with the CSPDT. Fine dexterity was reduced with the screwing action in CSPDT
Drabek *et al.* (97)	20	Vinyl	Grooved Pegboard Test	No effect on dexterity regardless of glove size used. Time to remove pegs was significantly quicker with best fit gloves.

2.6.3 Grip and friction

The frictional properties of medical gloves is an important factor which glove manufacturers should consider. It is these properties which allow for the users to ascertain grip and have a sense of force they are applying, which is imperative for the ability to carry out tasks such as holding tools and applying pressure to wounds. Friction is defined by the resistance to motion of objects, which move over each other. Therefore, grip relies on the properties of the materials in contact. At a fundamental level, the friction is determined by the contact of minute surface anomalies, known as asperities. These asperities can interlock on surfaces and increase friction or sit atop each other and reduce friction (103, 104). Two types of friction are commonly measured (105). Static friction is the amount of friction present between two stationary objects. When one object moves, in this case the hand or glove, the static friction is measured at the start of the sliding process. The sliding friction is known as the dynamic friction. Static friction tends to be greater than that of the dynamic, due to the increase in friction forces as the surface roughness' (asperities) locally weld (106). The addition of moisture can have a great impact on the friction, by separating the surfaces and reducing the friction (71, 107). This could be a problem with bare skin due to the presence of sweat glands and introduction of contaminants such as oils from pores (103, 108). c

Accurate force control for grip precision demands finer detailed information from mechanoreceptors in the skin. Thus, when these are blocked by a membrane, it would be reasonable to assume that grip force would be impaired (63, 73). Much of the work regarding grip is oriented at industrial applications and extra vehicular activity gloves for use in space (9) , with few looking at medical gloves. Gnaneswaran *et al.* (86) showed that when powder was present on the gloves, more grip force was exerted. This is presumably because the frictional properties of the gloves were lowered due to the presence of the powder. However, similar findings were reported in Shih *et al.* (73), Willms, wells and Carnahan (109), and Kinoshita (110), who reported that thicker NRL gloves made participants exert more grip force when picking up a desired load. They conclude that gloves should be thicker in order to retain a greater grip force. However, it has been shown that that thicker gloves impair sensitivity (41, 78). Park *et al.* (63) looked at the role of mechanoreceptors in force control and the effect of gloves on precision grip. The study found that there was a 20% increase in measured grip force when subjects lifted a heavy object after lifting a light object when gloves were not worn. This grip force was not significantly different when the same test was carried out with NRL gloves, suggesting the sensorimotor effects of gripping were not affected by the gloves. Only one study was located where there was a measured decrease in the grip force with NBR and vinyl gloves (111). Many of these studies appear to see an increase in force as beneficial, as grip is imperative for control. Although, these studies do not look at the effects of this force increase on the hands. It could be that this increase in grip, however slight, could affect fatigue on the hand and arm, thus affecting dexterity and performance. It should also be noted, that the over-gripping effect could be due to a reduced friction coefficient between the object and the hands when gloves are introduced. As with Willms *et al.* (109), assessing how much pressure is instinctively applied, and then how that adjusts overtime during a surgical procedure is required. However, assessing whether the change in load is down to the gloves or the tasks carried out during surgery itself could prove to be a difficult.

Many of the published studies looking at the frictional properties of medical gloves focus on surfaces that are impractical to the medical profession, such as glass and sandpaper (73, 112, 113). Mylon *et al.* (87) found no significant difference between NRL and bare hand friction with sandpaper but found a significantly lower friction coefficient with NBR. Carré *et al.* (90) studied the friction of surgical gloves on steel and found that the friction coefficients of NRL gloves were greater than the bare hand condition. This finding is different from Shih *et al.* (73), who noted that the coefficient of friction decreases when NRL gloves are donned. Laroche, Barr, Dong, *et al.* (114) looked at the static friction of wet NRL and NBR gloves on a variety of dental tool patterns. Greater friction coefficients for tools with knurled surface patterns were observed. Although this is the first test to incorporate real tool patterns with fluids, this could be greatly improved by having more realistic bodily fluids in contact with the gloves, such as blood and saliva (115). The study also did not include a control, such as no gloves or dry gloves to compare. A paper published by Anwer (116) includes the use of blood to assess friction modification in NRL gloves. They found that blood, and blood and water (1:1 mixture) increased friction coefficients when the compared to the dry state with NRL gloves. The friction tests were carried out on a surgical scalpel. Although a unique study, which is required in this area, a few issues are noted. The author states that friction increases as the blood starts to coagulate under mechanical stress. However, bloods from different sources and treatments have different rheological properties, including different viscosities and different shear rates, which will influence the frictional behaviour (117, 118). Furthermore, the temperature of the blood, which is not mentioned in the study, will induce a difference in coagulation properties, thus affecting the friction. However, this is the only study to date considering the effects that blood could have on the friction of medical gloves. In addition, the study found that double gloving induced a greater friction coefficient than a single layer. However, no explanation is offered as to why this may be. It is possible the frictional changes are due to the relative motion of the latex-latex interaction sliding within the gloves, causing a difference in friction. No statistics were performed to conclude that this difference is significant. Nevertheless, this study shows that consideration needs to be paid to the reason why gloves are worn, that is, for their protective barriers, and contaminants should be incorporated into future tests. This is a fundamental consideration, especially in surgical tasks where gloves are more likely to be in contact with bodily fluids, and then a wide range of tools. Including fluids into assessments would provide a greater significance to the results of any of the friction and grip studies being conducted.

The frictional properties of the inside of the gloves also requires consideration from glove manufacturers. Often a quick change of gloves is needed in fast-paced environments which can be made difficult with the presence of moisture (15, 119, 120). Roberts and Brackley (57) found that coating the glove with hydrogel gives a lower coefficient of friction than chlorination treatment, thus enabling easier donning. Pavlovich, Cox, Thacker, *et al.* (120) demonstrated that when hands were wet, the gloves became more difficult to don and greater force was required to pull the glove on, when compared to dry. However, in this study, the hands were wet, with no drying process involved. This is unrealistic of the real-world scenario of requiring a quick change of gloves. Damp skin has been demonstrated to have higher friction coefficients when compared to dry skin (121). As many issues lie with donning gloves with damp hands, this should be of consideration when assessing the frictional properties of the inner surface of glove materials (120).

Medical Glove Surface Interaction

In the studies where friction and grip are concerned, there is a disregard for surfaces which examination gloves encounter when in use. Medical gloves encounter a wide array of substances and surfaces in a clinical setting in particular. Therefore, these studies should be accounting for the materials that are contacted, allowing for a more targeted approach as to how gloves affect friction and grip. In order to do this, it must be understood what surfaces gloves most commonly come into contact with. All UK general practitioners (GP) are encouraged to provide minor surgical procedures to the populations they see. This generally reduces the pressure in the hospitals around the UK. These minor surgeries are all outlined in the Standard General Medical Services Contract (2009) (122). The minor surgeries contracted to be carried out in a GP office can be placed into one of two categories:

- Injections and aspirations: Drugs/vaccines injected into the body via a hypodermic needle and syringe. For example, the injection of cortisone into the foot to elevate plantar fasciitis pain.
- Excisions and incisions: removal of a small or large area of tissue. For example, the removal of a sebaceous cyst (excision) or the draining of an abscess (incision) (NHS, 2017).

The list of medical equipment used in these procedures is exhaustive, as is the list of general medical equipment nurses and doctors will interact with in hospitals and GP surgeries. Equipment most likely to be used is shown in Table 2.4. These have been chosen based on likelihood of contact in common minor procedures and general nursing healthcare, along with bodily fluids that are likely to be encountered.

Table 2.4. Tools and equipment used in minor procedures to give an overview of the surfaces and textures encountered.

Equipment	**Use/handling**	**Material(s)**	**Surface finish/textures**	**Bodily fluid(s) in contact (between glove surface and equipment)**
Disposable scalpel	Used to cut into tissues/samples for removal of foreign objects or implantation of devices. Pressure is applied to scalpels, as these are required to break the skin, but are equally extremely sharp (123, 124)	Disposable scalpels are composed of polystyrene handles with stainless steel blade. Metal scalpels, more often used for surgical applications are more commonly composed of stainless steel handles (124, 125)	Smooth top and bottom. Sides where the thumb and middle finger are placed have deep ridges present (125)	All major bodily fluids could be in contact with the scalpel after the initial breaking of the skin. Blood, mucus, saliva, etc.
Thumb tweezers/forceps	Used for suturing where required and removal of foreign materials (126)	Stainless steel (127)	Grooved/ridged patterns dependent upon the manufacturer (128)	Blood/saliva in some dental procedures. Possible blood exposure if used to hold back skin and/or extraction of foreign objects.
Syringe (with needles and cap)	Used for the injections of fluids into the body as well as the aspiration of blood and other fluids such as pus. The force applied to syringes is dependent upon the task and fluid being injected. The act is normally carried out slowly (124).	Polypropylene plastic syringes with a stainless steel needle (129)	Ridges on thumb press and where syringe is stabilised by index and middle finger(128)	Minimal risk of contamination. There is a risk of alcohol being in contact from alcohol wipes used to clean the site of puncture when taking fluids.

Scissors/handled forceps	Used for the handling and cutting of tissues and medical aids such as bandages and tape (128, 130).	Steel (124, 130)	Smooth on the handles where grasped (131)	Dependent upon the site with which these are being used. Frequently used to cut/make stitches, so it can be presumed blood would be in contact.
Curette	Used for the scraping and debriding of tissues (131).	Steel (114)	Textured – knurled (diamond shape, for example) or annular (circular grooves) (114)	Blood in most clinical cases, could be other fluids present depending on area of surgery (mucus and saliva). Presence of saliva in dentistry.
Tubing – probes, catheterisation, suction, dialysis, and oxygen tubing.	These tubes have many applications. Some are used to aid breathing in intubation or as a flow path for bodily fluids out of the body or drugs into the body, such as blood cleaning in dialysis. These tubes are usually attached at their end, one normally to the patient/a device in/on the patient and an instrument (132)	Poly vinyl chloride (PVC), polyethylene, silicone (132)	Smooth (131, 132)	May be in contact with blood and or/excretive bodily fluids such as urine and faeces.

The list in Table 2.4 is not exhaustive as many other surfaces are contacted, and many more contaminants would be present. The surfaces of some of these equipment are manufactured to be smooth, whereas others are manufactured to contain spaced grooves to allow enhanced grip (e.g. a scalpel). Whilst the friction studies conducted show a difference in the friction of gloves, the surfaces they use are not representative of the surfaces which are normally encountered with medical examination gloves.

2.6.4 Double gloving

Throughout the literature, it is recommended that where surgery is a high risk due to diseases, such as HIV, two layers of gloves are worn to minimise exposure. Much of the research on double gloving is centred around puncture indication during surgeries (i.e. using different coloured gloves to indicate the outer glove layer has ruptured) (133). Johnson *et al.* (75) and Kopka *et al.* (41) both show that dexterity decreases when thicker gloves are worn. Thus, it would seem reasonable to believe that dexterity would be more affected when multiple layers are worn, as the thickness is increasing which could restrict movement. However, Webb and Pentlow (134) found that double gloving did not affect dexterity when assessing knot tying. Fry *et al.* (77) also determined that there was no statistically significant difference in performance when subjects wore two glove layers compared to one when completing the Purdue Pegboard test. There are, however, opposing results with regards to the effect of double gloving on tactile sensitivity. Novak *et al.* (67), Shih *et al.* (73) and Han *et al.* (78) show that there is a loss in tactile sensitivity when assessed by monofilament or two-point discrimination. On the other hand, Fry *et al.* (77) and Webb and Pentlow (134) show no statistical difference in two-point discrimination between one and two glove layers. Germaine, Hanson, and de gara (135) demonstrated that double gloving is not favoured amongst surgeons. Out of the 170 medical staff asked, when practice recommends that they double glove, 78 said that they do not as it decreases their dexterity and 62 said that it was not comfortable. Regardless of the evidence involving the practicality of double gloving during high-risk surgery, there is little discussion in the literature as to how to double glove. Hollaus, Lax, Janakiev, *et al.* (136) discuss using the same sized gloves as well as whichever size makes the user comfortable. However, much of the literature focuses on the method used in Fry *et al.* (77) and recommend double gloving by using a larger inner layer glove and a smaller outer layer glove. The authors suggest this reduces dermatological issues but does not offer any insight into how dexterity and tactile feedback may be affected via this method.

2.6.5 Donning

The donning of medical gloves is a relatively unexplored area in the literature. As previously stated, much of the research conducted in glove friction applies to the outer interaction with the environment, such as glass (113). Glove donning is a complex process due to the stretching and bending of the materials as they are being pulled. The hand is inserted to the glove and the other hand is pulling the material/holding it in place. If the glove gets stuck, it is common practice to stop and manipulate the glove to aid the process of the glove going onto the hand. However, this task is made increasingly difficult upon the addition of moisture (15, 57, 119, 120). Previous studies looking at glove material donning have used loads as an assessment of donning 'ease'. Cötë, Fisher, Kheir, *et al.* (119), Pavlovich *et al.* (120), and Edlich, Heather, Thacker, *et al.* (15) have looked at the loads used in donning medical gloves. By attaching the cuff of the glove to a ring, in which there are load sensors, they found they could measure the force applied to don the gloves. The studies collectively found load ranges between 29-78 N were being used to don the gloves when the hand was in a wet condition. In all studies, the wet condition required a lot of water present on the surface of the hands, making the studies unrealistic to a donning scenario. Glove donning with 'wet' hands tends to arise as a function of improper drying or sweat generation, rather than hands having water dripping from them. The loads used in these studies are extremely high, so much so, that in Pavlovich *et al.* (120), the gloves tore under the applied loads and no measurements were recorded in over half of the gloves used. Furthermore, the studies do not consider the realistic donning process, in which the glove is not in a fixed cuff position held in one location. Much of the time, the gloves are being stretched in different places. It is unclear in the studies if the subjects were able to use their other hand to pull the material in places where the glove did not fit. If not, then more force would be applied to make the hand slide down the glove when the material is stuck to the hands. These studies appear to be more about comparing how much force is needed with different internal glove coatings, rather than looking at how 'easy' it is to don the gloves. It is reasonable to assume that that less force used to don the gloves would make the glove easier to don. However, these studies lack application to the processes used in the donning of gloves. Furthermore, very few studies have been produced linking the internal coatings used on medical gloves to the donning process.

There are many companies stating the benefits of different coatings and how chlorination helps the donning process by smoothening the surface, but little literature is available on this. Much of the work conducted in this area is protected under patent, thus it is unknown whether there are significant rigorous tests being conducted which could be related to realistic working conditions gloves are used in. Roberts and Brackley (137) looked at the friction of medical gloves on the inner surface with skin at a load 4N and a glass surface at 0.32N. Roberts and Brackley (57) also compared the friction of hydrogel gloves in a similar study, using a load of 0.4N with fingers. However, no reasoning is given for the selection of these loads. The authors find that generally, the hydrogel coated gloves are preferred, and the friction coefficients tend to be lower than the chlorinated gloves. It should be noted that all these studies are investigating the natural rubber latex gloves with different applied coatings. No other gloves appear to have been used. It is important to include other materials in these types of studies, as the market trend shift due to the increasing demand for non-latex gloves, these literatures will allow for up-to-date assessments of the available gloves.

2.6.6 Durability

Under EN 455 guidelines, gloves are tested for their durability and puncture resistance. The puncture resistance/durability is inferred from the force required to break the materials, as discussed in the glove standards (see Section 2.4). In industry, durability on gloves can be tested via the use of abrasion resistance, using soft pads which are placed onto the material, and relative movement wears the gloves over time (138). As the primary function of gloves is to act as a barrier, and protect the hands, several studies exist looking at the barrier integrity of the gloves. Since the introduction of non-latex gloves, much of the research has focused on comparing glove materials. Many tests look at abrading gloves with abrasive materials such as grit (139), which do not represent the realistic working conditions these gloves are used in, when in a medical setting. It is appreciated that gloves are not used solely for medical purposes. However, this study compares the grit durability method with a simulated clinical study. The simulated clinical work is a good indicator as it shows the durability of gloves when in-situ. However, this is impractical to the manufacturing industry (139, 140). Further tests investigating the failure rate of gloves whilst in surgeries have been conducted (136, 141, 142). Many of these tests are looking at NRL gloves. Much of the earlier research focuses on PVC gloves, showing that the NRL material has lower failure rates (35, 139, 143, 144). Further research looking at NBR gloves found that NRL and NBR had similar failure rates (64, 145). Studies which focus on the failure rates of gloves in surgery draw comparisons to other studies to indicate that gloves are either more durable, or less durable. However, there are a variety of surgeries used between studies (136, 146, 147) ranging from oral surgery, to osteology, where bones are broken and many more tools are used. There is also a tendency to statistically compare the perforation rates. However, in some studies there are orders of magnitude difference between the duration procedure as well as the total number of procedures included, thus making for an unfair comparison between studies, leading to erroneous conclusions. Studies have shown that gloves tend to wear out between the thumb and the index finger, as this section of the glove undertakes a greater amount of mechanical strain. These also highlighted the potential failure for examinations gloves are at the joints of the knuckles (138, 148). However, little regard is paid to the nature of these gloves in most of these studies. Those looking at novel durability methods compare gloves with other studies, although no thicknesses are published in some of the work (139). It could be that the differences in results between some of the gloves are due to the thickness, rather than the material itself, as previously highlighted (12).

2.7 Size and fit

Glove fitting is a vital part of both the donning process and the practicality of wearing gloves. Gloves should freely fit the contours of the hands, and act like a second skin layer. If too large, the glove will be easier to don, but the excess loose material can cause issues with dexterity and sensitivity. If too small, the gloves can be difficult to don and restrict movement of the fingers (99). No studies could be found which investigate glove sizes, specifically regarding how they are sized and how that relates to the general population. The government provides protective glove size recommendations for Europe and the United States only, but no information is given as to how these sizes are ascertained. To determine the best fit of a glove, two measurements are required, which are shown in Table 2.5 (149), as provided by the HSE. Firstly, the hand should be measured from the base of the palm to the tip of the middle finger. This produces the 'finger length'. Secondly, the 'palm circumference' is measured just below the knuckles. These two measurements provide a glove size for the hand. This protocol appears to be universally adopted. However, no reference is provided as to where this protocol is obtained.

Table 2.5. Finger and palm measurement sizes for selecting the best sized glove (149).

Finger length (cm)	Palm circumference (cm)	Size
16.0	15.2-17.8	XS
17.1	17.8-20.3	S
18.2	20.3-22.9	M
19.2	22.9-25.4	L
20.4	25.4-27.9	XL
21.5+	27.9+	XXL

2.8 Paper grading

To identify gaps where research is required with regards to glove performance assessment, a paper grading system has been adapted from Harmon and Lewis (150) and Watson, Christoforou, Herrera, *et al.* (151), who found that study design and reporting of key findings was flawed across the field of tribology. The aim of this grading differs from these by the way of trying to identify areas where research should be focused in the future. The grading is focused on application of research to relevant systems within the clinical environment and categories differ from those used in previous papers in order to reflect the aim and the practices used in this area of research. It is noted that this way of grading papers is subjective, thus the grading has been kept to matter-of-fact as opposed to subjective analysis (i.e. focusing on participant number and statistical analysis as opposed to the experimental design). It is important to note that not all of these criteria will be applicable to the study designs for this grading. This means that a study which scores highly is not essentially a good study, but a study that fulfils more of the criteria. Similarly, a high score may include all criteria, but whether the entire study is fundamentally flawed will not be determined by this grading. The research papers used in this review have been graded according to the following criteria:

(1) Repetition of work: does the study repeat tests to obtain an average result?

(2) Number of participants/samples: does the study have a respectable number of participants/tests? (The average participant/sample number throughout the glove assessment studies is 30, thus this has been used as a benchmark. Anything <30 does not meet these criteria).

(3) Statistical analysis: has a statistical analysis been conducted?

(4) Conclusions: are the conclusions in the paper based on the results presented?

(5) Representative simulation: does the work simulate a clinical and/or surgical scenario? E.g. suturing, pulse-feel, etc.

6) Glove material: have multiple glove materials been studied?

A grade ‘A’ constitutes as fulfilling 5–6 of the criteria; grade ‘B’ constitutes fulfilling 3–4 of the criteria and grade ‘C’ constitutes 0–2 of the criteria. A graphical representation of the results is displayed in Figure 2.10. Much of the research is focused on durability; this is most likely to be because the durability of medical gloves is significant to function. Thus, this is an area of primary focus. However, these assessments have focused mainly on obtaining and testing gloves after surgical procedures have been performed. As there are a great number of different surgical procedures, each with different tasks and different periods of glove wearing, this may result in incomparable data within the literature. Very few studies focus on the grip and frictional properties of medical gloves. It is recommended that further research should be carried out into the frictional properties as well as the performance effects of tactile sensitivity and dexterity of gloves. Although many of the studies here have good grades by these defined criteria, many of the methodologies lack standardisation and do not have a control or a baseline reading of the gloves (8, 35, 71–75, 77, 78, 80, 83, 84, 41, 85–88, 90, 92–96, 42, 97–101, 109–113, 57, 114, 116, 138–144, 146, 63, 147, 148, 152–159, 67, 160, 68–70).

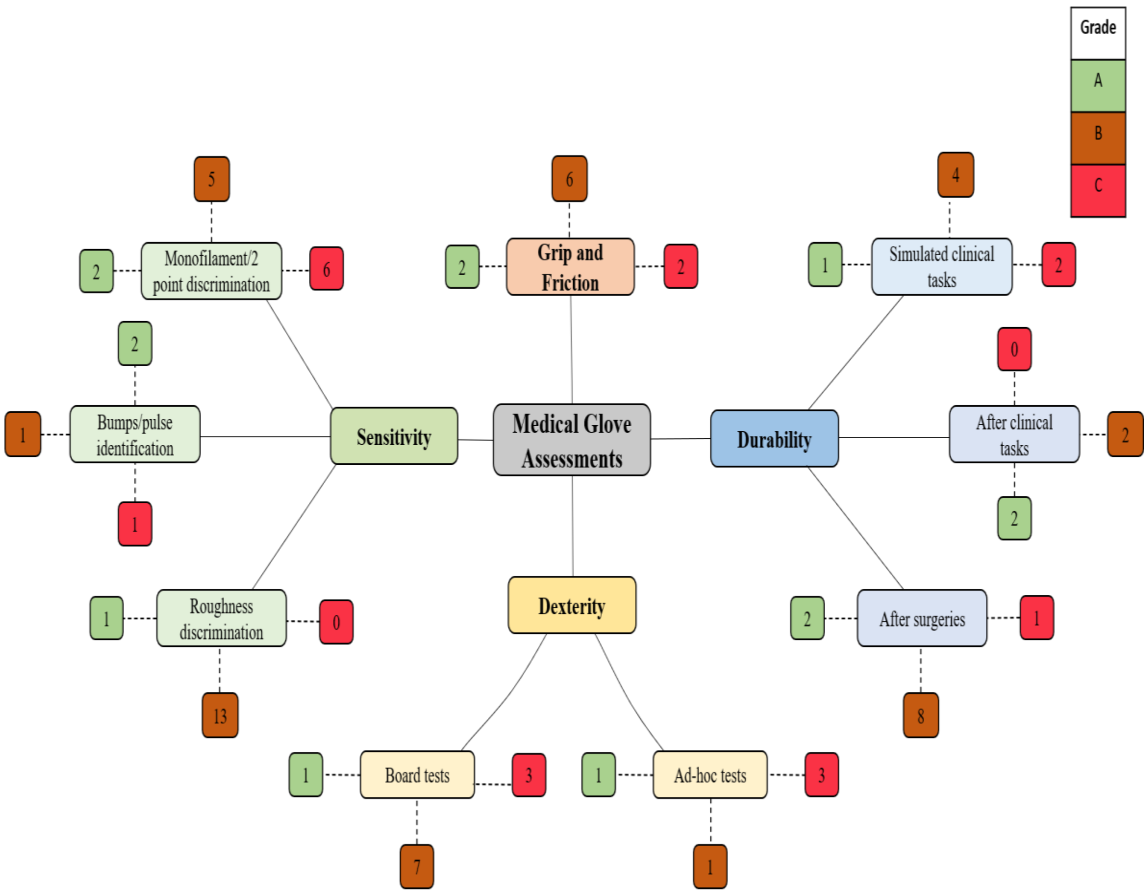


Figure 2.10. Grading of glove related papers to assess gaps in knowledge.

2.9 Conclusions

Overall, the literature suggests that sensitivity, friction, and grip are affected when medical gloves are worn, but dexterity is not. The differences in results between studies of the same tests may be a result of the difference in glove properties, arising from differences in manufacturing. Many studies do not discuss this possibility, and numerous studies looking at dexterity do not assess thickness of the gloves. Linking the key manufacturing parameters to performance will give better information about which processes affect performance. When assessing medical gloves, the purpose of the barriers should be considered in the tests. Thus, contaminants should be incorporated where possible. Understanding how these contaminants affect the frictional properties of the gloves will provide insight into how medical gloves perform. Including the assessment of a desired performance characteristic into the manufacturing process will ensure the production of high-quality gloves that are fit for purpose.

Chapter Three: Questionnaire

In the first instance, it is important to establish the issues surrounding medical glove use. Exploring user perceptions is key to unlocking the areas where problems may occur. In the literature review in Chapter 2, it was shown that there are flaws in previous work, as the studies conducted lack the realistic conditions gloves are used in. Therefore, it is important to establish what gloves are in contact with, which may contaminate them, and affect their performance. The areas where performance is then affected can then be explored in more detail in order to further assess the effects examination gloves have on users.

3.1 Introduction

Very little has been published on the perception of how examination gloves affect the user. This leaves very little understanding about how gloves affect the users. Mylon, Lewis, Carré, *et al.* (7) used a focus group of thirty four NHS medical staff to ascertain areas where perceived problems lie with surgical gloves. It is important to note that this study focused on surgical gloves, which are different from examination gloves in that they are designed to be worn for longer periods of time, and have more precise sizing (161). Examination gloves, however, are to be worn for shorter time periods and range in sizes (extra small, small, medium, large and extra-large) (149). Many studies show gloves have an effect on the performance of the user when carrying out tasks (6, 12). Furthermore, gloves have been shown to cause issues with contact dermatitis and the skin drying out when gloves are worn for longer periods of time, or if any allergies are present (34, 162, 163).

In most cases, gloves are used to protect the user from contaminants (such as blood), but there is little literature assessing how these contaminants affect performance (114, 116). Furthermore, there is no literature suggesting what contaminants gloves commonly come into contact with. To determine how these contaminants are affecting the performance, it is important to establish the nature of these contaminants which are coming into contact with the gloves. Examination gloves are used extensively throughout various sectors. Arguably, the most important of these sectors is the area of medical care. Although, many other sectors rely on the performance of examination gloves for health and safety. For example, forensic scientists rely on examination gloves to protect evidence from contamination (164) as well as protecting themselves from contaminants, such as blood. These gloves need to provide the same level of dexterity and sensitivity that any medical care professional would require, in order to fully evaluate physical evidence.

3.2 Aim and scope

It is thought that, as few studies can be found regarding glove perception, further questions should be asked in order to uncover further issues surrounding gloves. As observed in the literature review in Chapter 2, there is a huge gap in studies relating to the performance of examination gloves once exposed to contamination. In order to assess this, it was pertinent to obtain information regarding what contaminants are contacted amongst glove users, what the perceptions of the gloves are and what issues they are facing with the two most common glove materials. Thus, the aim of this study is to gather views on the perception of examination gloves amongst common users. The purpose of this study is not to obtain differences on the glove preferences, but rather to obtain information on what glove materials are being worn routinely, the perception of the gloves being used, the ease of donning and doffing the gloves, the contaminants they come into contact with, and how the users perceive the way that contamination affects the performance when carrying out tasks.

3.3 Methodology

3.3.1 Questionnaire

Due to the regulations and restrictions surrounding research into medical devices within the NHS, it was decided that data would be gathered via questionnaires. Although limitations exist with questionnaires, in terms of user response and bias from the questions (i.e. leading questions), they are effective ways to reach a wider range of participants quickly and efficiently, without the requirement of obtaining participants for focus groups. The use of focus groups was discussed; however, it was decided that as the aim was to reach a wider audience a questionnaire would be more efficient. Attaining a wider audience would give a more accurate and varied view of the kinds of issues that arise from glove use. The research received ethical approval from the Department of Mechanical Engineering (No: 022731).

Participants were approached by e-mail, as well as verbal communication, aimed at professions which require frequent glove use (e.g. private medical centres, dentists, testing laboratories, police forces, forensic laboratories etc.) based in the United Kingdom. In addition to this, the questionnaire was also posted on nursing/medical/laboratory forums in the United Kingdom (.co.uk domain). Participants were invited from various job roles to take part in the survey. The only requirement for participation was that either NBR and/or NRL examination gloves had to be routinely worn in order to conduct their daily tasks. Only NBR and NRL were asked about this study due to trends in the market leaning towards a shift from NRL material to NBR (38). As discussed in Chapter 2, other glove materials are used (PVC and chloroprene), but these are less frequently encountered. The participants were asked to fill out a questionnaire consisting of eight questions, based on the perceived issues with gloves obtained from the literature review in Chapter 2 (dexterity, sensitivity, durability etc.). The questions were also asked to further explore the issues brought up by the focus group in Mylon *et al.* (7), and then questions were asked to see whether these issues were present when gloves were contaminated. Some of these questions asked were presented with set multiple choice answers, using the answers which were similar to those obtained from the focus group in Mylon *et al.* (7). This was to entice more participants by making the form easier and quicker to complete. Participants were asked the following questions:

1. What is your job title?
2. Which glove material(s) do you routinely wear?
    - Latex
    - Nitrile
    - Other (please specify)
3. Regarding LATEX medical gloves, if you have worn this material currently/previously, which of the following do you think are ISSUES with the gloves (please state other issues where applicable).
    - Fit
    - Comfort
    - Dexterity (ability to carry out tasks)
    - Sensitivity
    - Grip
    - Ability to put on
    - Ability to remove
    - Tearing
    - No issues
    - Other (please specify)
4. Regarding NITRILE medical gloves, if you have worn this material currently/previously, which of the following do you think are ISSUES with the gloves (please state other issues where applicable).
    - Fit
    - Comfort
    - Dexterity (ability to carry out tasks)
    - Sensitivity
    - Grip
    - Ability to put on
    - Ability to remove
    - Tearing
    - No issues
    - Other (please specify)

5. What are the most common contaminants that these gloves encounter in your job role?
    - Blood
    - Urine
    - Saliva
    - Mucus
    - Other bodily secretions (please state the nature)
    - Liquid drugs (please state nature of drug)
    - Powders (please state nature of powder)
    - Other (please state)
6. When LATEX gloves are contaminated with these substances, what issues does this cause?
    - Comfort
    - Dexterity (ability to carry out tasks)
    - Sensitivity
    - Grip
    - Ability to remove
    - Tearing
    - No issues
    - Other (please specify)
7. When NITRILE gloves are contaminated with these substances, what issues does this cause?
    - Comfort
    - Dexterity (ability to carry out tasks)
    - Sensitivity
    - Grip
    - Ability to remove
    - Tearing
    - No issues
    - Other (please specify)
8. Do you feel there are any issues with carrying out specific tasks because of the medical gloves you normally wear? E.g. it is more difficult to open a box with gloves on.

To limit response bias (tendency to give false answers), the questionnaire was completely anonymised, with no names or any personal data being gathered in conjunction with the answers provided.

3.4 Results

In order to show the frequency of responses the results are displayed either as a percentage or the total number of user responses. A total of 172 useful responses were obtained over a period of five months. This number did not include seven responses where the respondents did not answer any of the questions.

3.4.1 Respondent roles

The different roles of the questionnaire responders have been categorised into job sectors and displayed in Figure 3.1. Over half of the respondents worked in a clinical role as a nurse or doctor (n=100). Other respondents came from the health-related fields of dentistry (n=14), veterinary (n=11), care (n=12) or were medical students (n=5). Collectively, these roles make up a total of 82% of the respondents. The remaining 18% of respondents had either a forensic, medical, or non-stated field laboratory technician role (n=30).

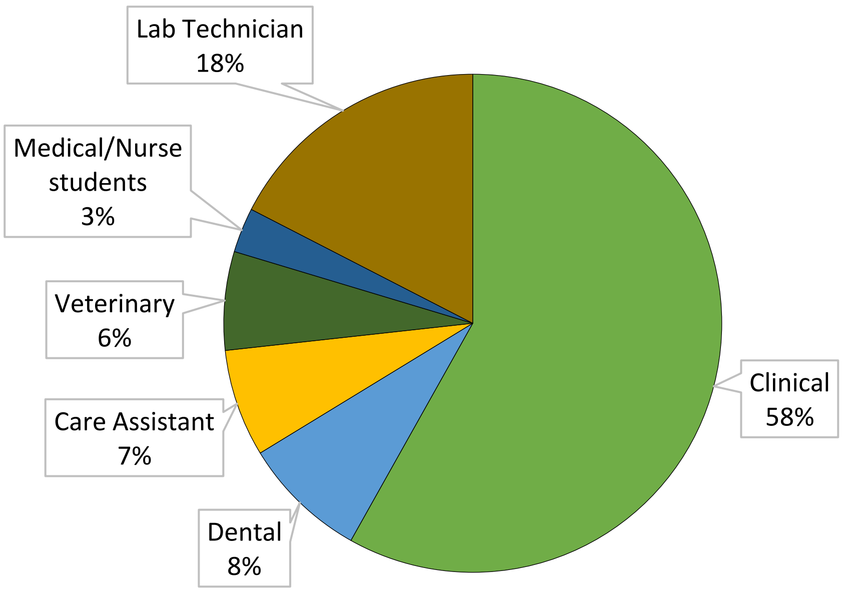


Figure 3.1. Respondents of questionnaire by job sector (n=172).

3.4.2 Glove materials

Participants were asked which examination gloves they routinely wear in their day-to-day work. A total of 102 of the respondents said that they used the NBR gloves, whereas 66 respondents stated they used NRL. Three respondents stated they use vinyl routinely, two of which were in the clinical field (nursing) and one a care assistant. These results are displayed in Figure 3.2. Only one person stated they used chloroprene gloves. None of the respondents indicated they did not know what material they routinely used, and all respondents indicated they routinely wear only one type of glove. Some of the users of NRL, however, did state they used NBR where NRL allergies are present in patients (n=12).

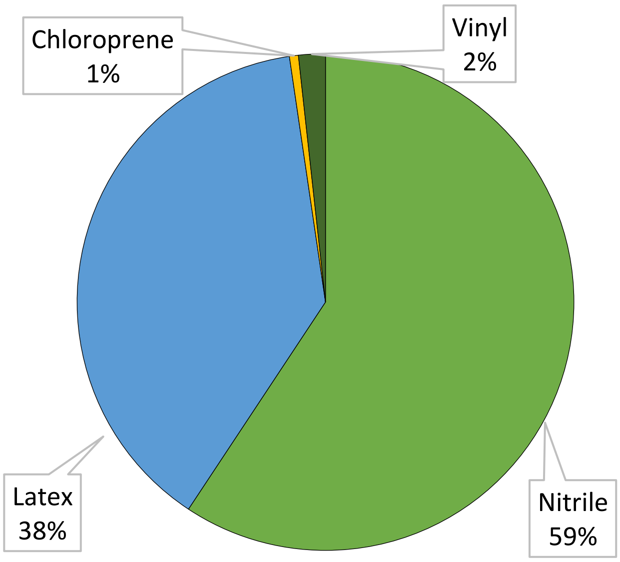


Figure 3.2. Gloves routinely worn by respondents (n=172).

3.4.3 Contaminants contacted

Figure 3.3 shows the responses for what contaminants are frequently encountered. Many of the respondents reported exposure to multiple contaminants. The contaminants encountered has been broken down by job sector and shown in Section 3.4.4. Overall, blood is indicated to be the most contacted contaminant (n=149) followed by: urine (n=95); medical disinfectants (n=81); saliva (n=68); liquid drugs (n=54); water (n=52); sweat (n=50); faeces (n=46); powders (n=44); mucus (n=40); pus/discharge (5); vomit (n=1); dirt(n=1) and food (n=1). Where powders or liquids were indicated, respondents were prompted to state what type of substance was touched (i.e. oily liquid or fine powder). The results of this are shown in Figure 3.4. These responses come mainly from lab technician roles, where finer powders are contacted. Some respondents also indicated they have regular contact with granular powders, but the nature of these powders was not disclosed. In terms of liquid drugs, it appears there are three categories these drugs fall into which are solvent, watery, or oily.

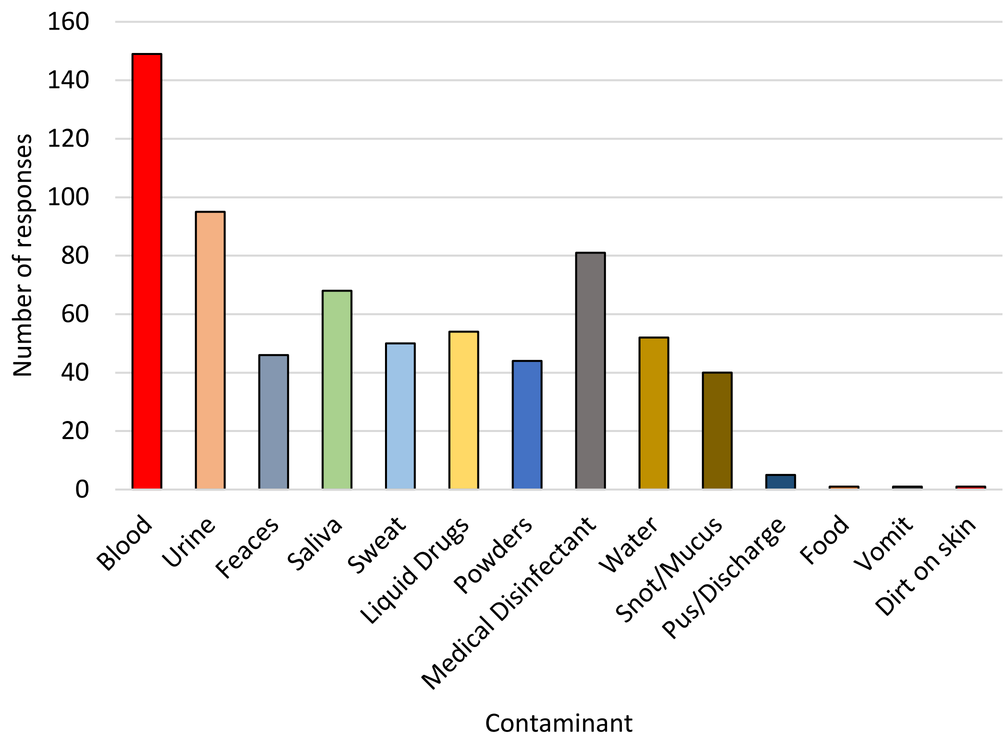


Figure 3.3. Contaminants coming into contact with medical gloves used throughout the various fields.

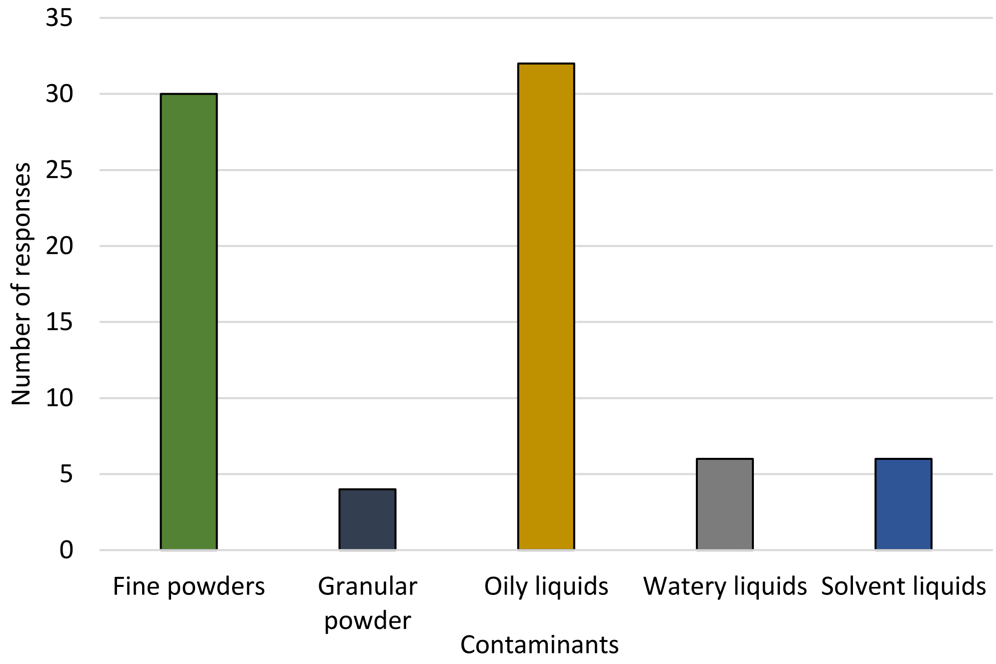
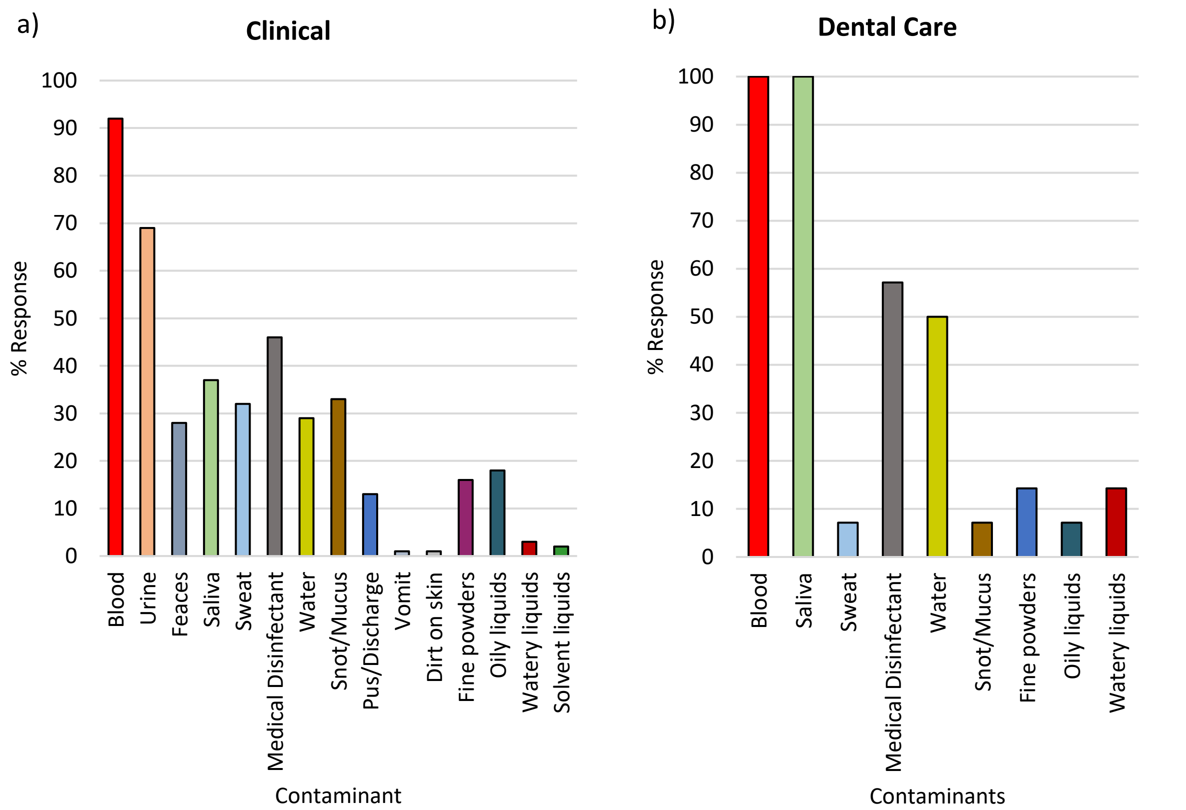


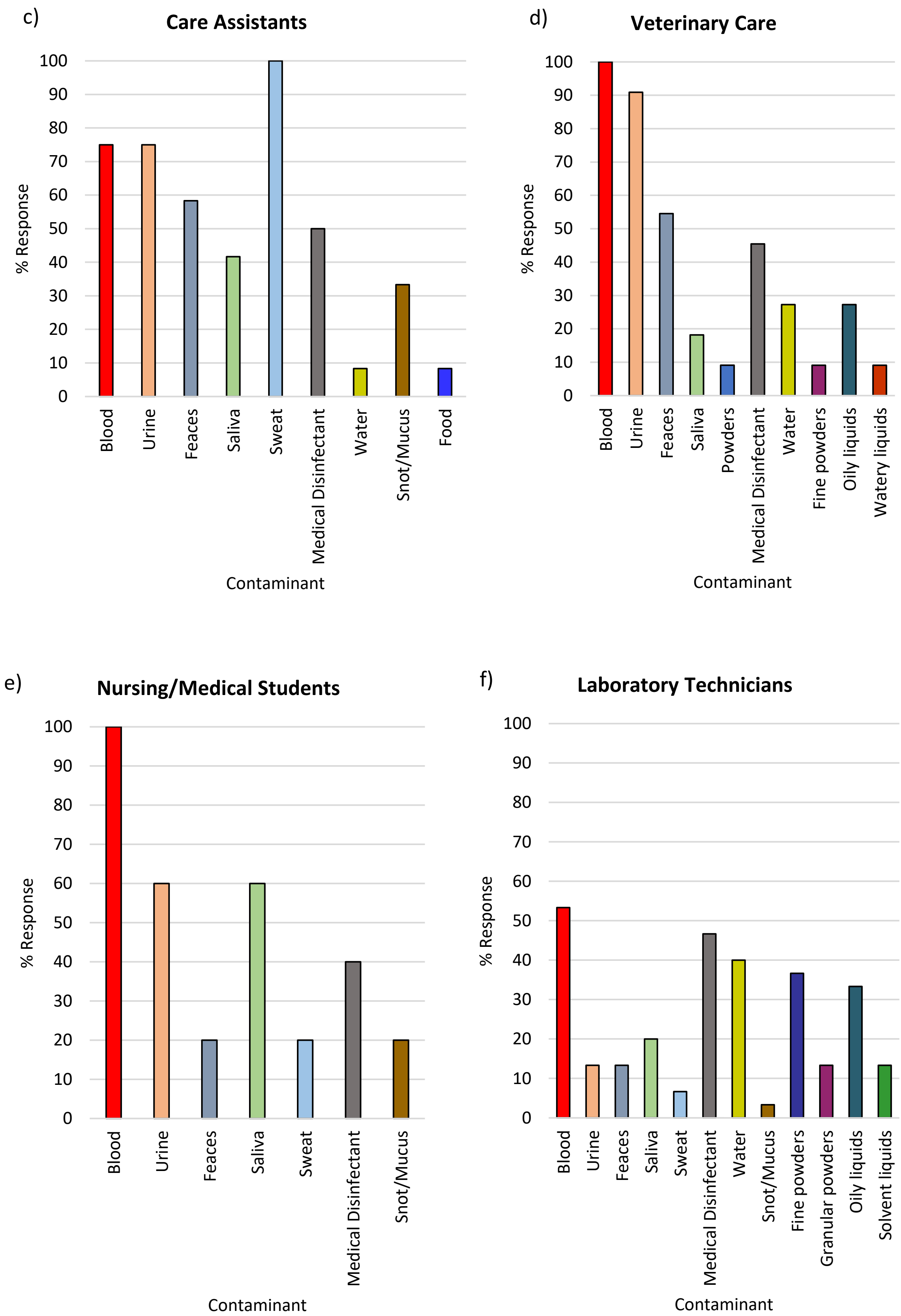
Figure 3.4. Liquid drugs and powders contaminating gloves as indicated by respondents.

Contaminants by sector

Contaminants have been broken down into the job sectors to show the variation of contaminants by role and shown in Figures 3.5. The most varied of the contaminants is shown in the clinical sector

(Figure 3.5a) where the gloves are exposed to all of the contaminants shown in Figure 3.3. Also, as indicated by the compilation of responses in Figure 3.3, blood exposure is prevalent throughout all job sectors. All (100%) of workers in the clinical sector stated they had regular exposure to blood, along with dental (Figure 3.5b) and veterinary care (Figure 3.5d). Saliva is also common throughout the varied job sectors. Many respondents from the lab technician role stated they were contaminated with fine powders from illicit drugs (n=30). On the other hand, respondents from the clinical field stated they had drug residues from tablets (i.e. paracetamol) contaminating the gloves. Some respondents also indicated they had contact with granular powders. However, they did not state what the nature of these powders were (n=4). Lab technician and clinical respondents also indicated contact with oily liquids such as steroids (e.g. testosterone) (n=32) and watery liquids (n=6), as well as solvents (n=6). The responses for each role are to be expected, e.g. more bodily fluids in the clinical, than in the laboratory roles. The result that stands out more, is the sweat in the dental sector (7%, Figure 3.5b). It is unclear how sweat would be exposed to medical examination gloves in a dental setting, as the oral cavity is the area where most activity would take place. However, there could be issues with stabilising patients' heads, which could contaminate gloves with sweat.





Figures 3.5 (a-f). Breakdown of all contaminants contacted by job sector.

3.4.4 Perceived issues with NRL and NBR gloves

Four of the 172 respondents stated they had never worn NRL or had NRL allergies. Also, nine of the respondents stated they had no issues; thus, the NRL results are displayed as issues amongst the 159 respondents. In the NBR gloves, 10 respondents stated they had no issues and 2 stated they have not worn NBR gloves before. This brings the total number of respondents for the issues with NBR to 160. The results of both NRL and NBR are shown in Figure 3.6. In total there were 429 responses to the issues regarding the NRL gloves and 597 for the NBR gloves. The issues perceived encompass both material issues (e.g. stiffness) and the performance (e.g. dexterity). The major issue reported with both gloves is the loss of tactile sensitivity (NRL n=77, NBR n=94). Table 3.1 shows the results and the between the number of responses with each issue. The greatest differences are noted in the thickness, ‘elasticity’, and dexterity between the two glove types. Due to the comments surrounding the elasticity (e.g. more stretchy/stronger), it is likely that the respondents were referring to the stiffness of the material.

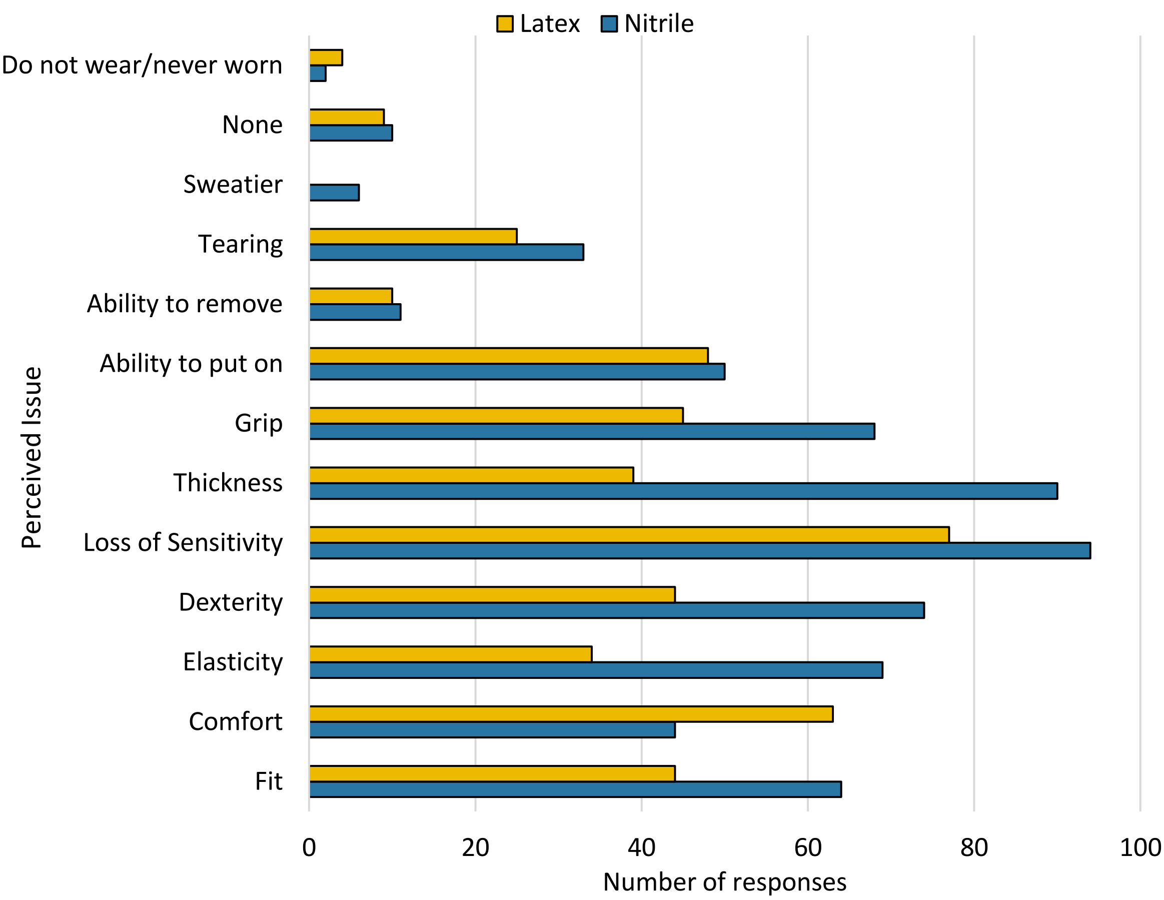


Figure 3.6. Results obtained from questionnaire regarding issues perceived with NBR and NRL gloves.

Table 3.1. Differences in response volume for issues between NBR and NRL gloves.

Issue	No of responses NBR	No of responses NRL	Difference
Fit	64	44	20
Comfort	44	63	19
Elasticity	69	34	35
Dexterity	74	44	30
Sensitivity loss	94	77	17
Thickness	90	39	51
Grip	68	45	23
Ability to put on	50	48	2
Ability to remove	11	10	1
Tearing	33	25	8
Sweatier	6	0	6
No Issues	10	9	1
Do not wear/never worn	2	4	2
Total responses	597	429	168

3.4.5 Perceived issues with contaminated gloves

Figure 3.7 shows the responses regarding medical glove use once they have been contaminated with the powders/fluids stated in Figure 3.4. The results are shown in Table 3.2, which shows that fit, dexterity, and sensitivity loss have the greatest differences between the two glove types. In the NRL, a total of 402 issues were reported, compared to 527 issues for NBR. When NRL and NBR gloves are contaminated, most issues arise with regards to grip (NRL n=101, NBR n=119); tactility loss (NRL n=82, NBR n=105) and dexterity (NRL n=73, NBR n=107). A total of forty respondents for the NRL, and fifty-six respondents for the NBR, stated there were issues with the 'elasticity' after contamination. More issues are reported in the NBR than the NRL, except in the issue of tearing (NRL n=23, NBR n=17). Overall, it is shown that more issues exist for the NBR gloves.

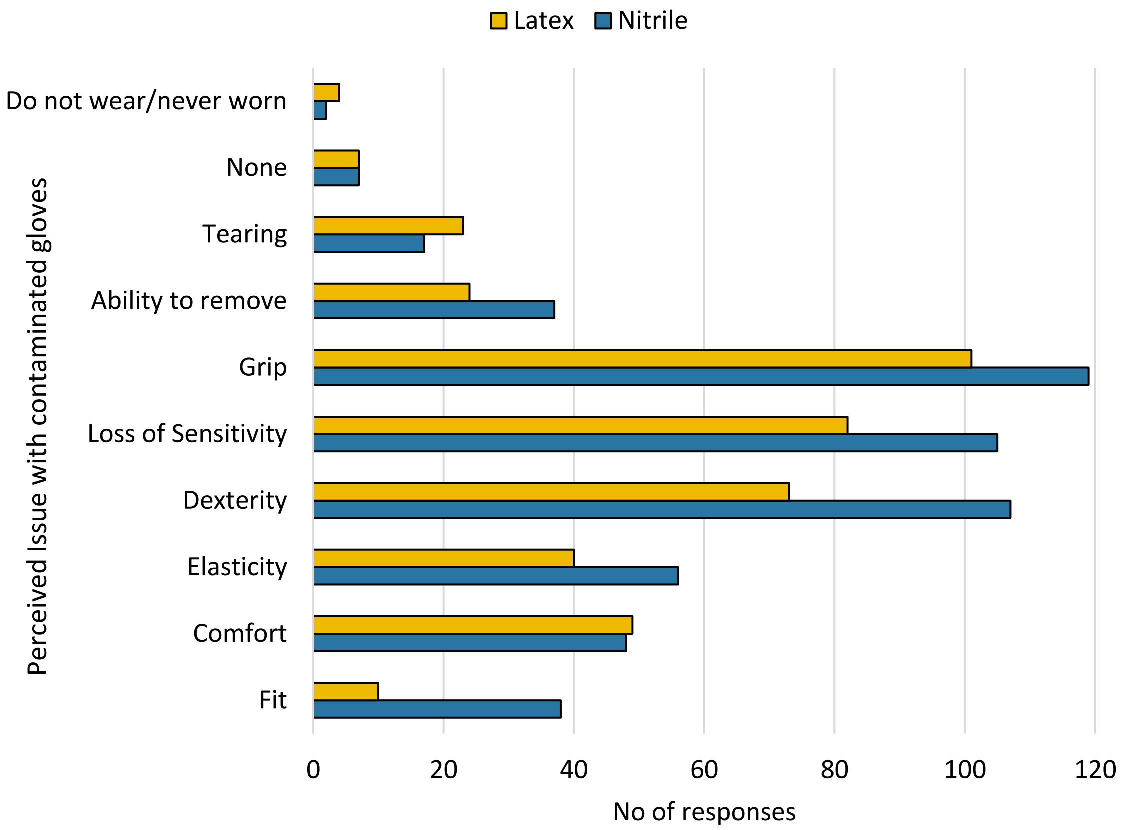


Figure 3.7. Results obtained from questionnaire regarding issues perceived with NBR and NRL gloves once contaminated.

Table 3.2. Response volume for issues between NBR and NRL gloves once contaminated with substances indicated in Figure 3.4.

	No. of responses		
Issue	**Contaminated NBR**	**Contaminated NRL**	**Difference**
Fit	38	10	28
Comfort	48	49	1
Elasticity	56	40	16
Dexterity	107	73	34
Loss of Sensitivity	105	82	23
Grip	119	101	18
Ability to remove	37	24	13
Tearing	17	23	6
No issues	7	7	0
Do not wear/never worn	2	4	2
Total	527	402	125

3.4.6 Further issues

When prompted to discuss further issues where gloves may affect specific tasks, 49 respondents did not answer or responded with no further issues. Many of the remaining comments expanded on the issues previously mentioned. For example, some respondents stated that the gloves were 'too slippery' and saying NBR was thicker, and more uncomfortable rather than reporting on a specific area they feel is affected. Although the question asked was to name specific tasks, there were only eight specific tasks identified. The remaining issues fall into problems such as: slipping of fingers inside the gloves, changing gloves, sweat generation, and size/fit of the gloves. All of the results are displayed in a sunburst diagram in Figure 3.8. An attempt has been made to identify and split up specific gloves where they have been stated. However the majority of comments did not state a particular glove material.

Figure 3.8. Diagram showing range of comments regarding specific issues with gloves. 'Not stated' indicates no specific material was given in the response.

Major issues identified are around the size/fit of gloves (n=25) as well as the changing of gloves (n=24). Where fit was mentioned, many respondents also commented on the slipping of their fingers inside of the glove. This was reported to cause issues in forensic laboratory respondents, as the materials cause them to incorrectly identify bumps and striations on materials. Also, in a clinical setting, there were comments focused on slipping affecting respondents' ability to carry out port connections where gloves are worn. There were 24 respondents who expanded on the donning incapability, stating it was extremely difficult to don gloves once any moisture was present on the hand, hindering their ability to carry out further tasks due to ill-fitting gloves. These issues are highlighted in Figure 3.9. Other comments included the colour of NRL was not nice once it was exposed to sweat in the hand (latex staining, n=2) and gloves made the hands sweatier (n=9). Which is a common issue noted in NRL gloves, whereby the chlorination treatment of the gloves causes them to yellow, even more so on exposure to sweat (14). When specific material issues were mentioned, most of these focused on NBR tearing (n=10), causing gloves to be changed which is time consuming. Along with this, comments appeared around NRL being 'too elastic' (less stiff) in nature, and snags easily (n=7). This reportedly leads to issues with glove tearing, snapping back onto the skin and sometimes misidentification of evidence in forensic laboratory tasks.

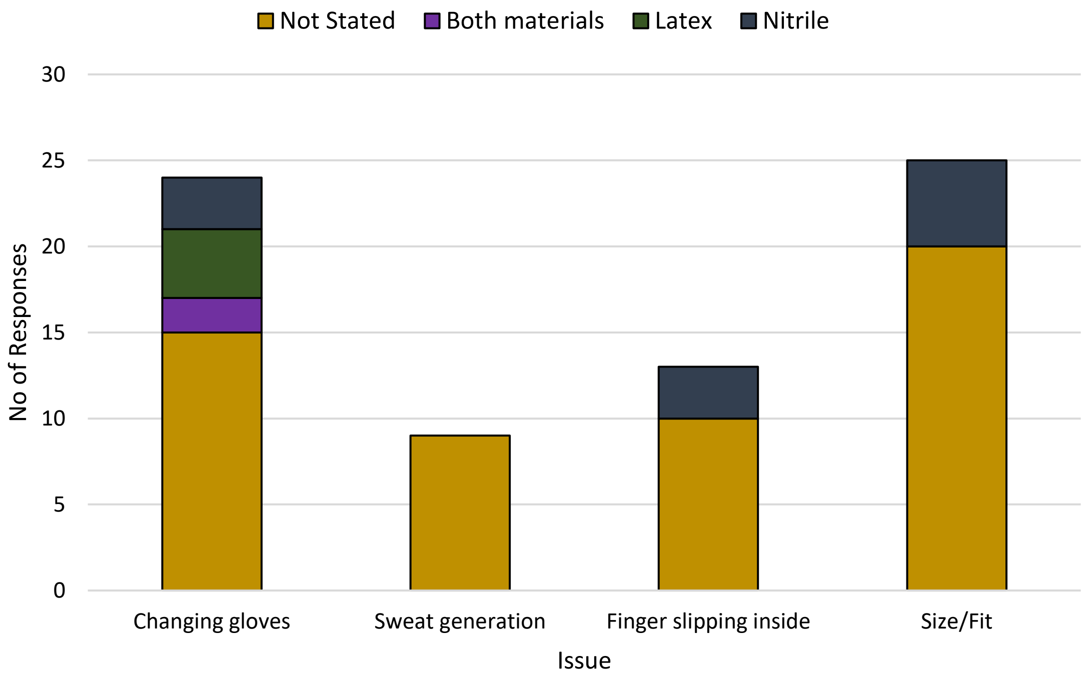


Figure 3.9. Breakdown of the responses surrounding issues from the comment section of the questionnaire. 'Not stated' indicates that no specific glove was given in the response.

Comments regarding specific tasks have been split into two sections; dexterity and sensitivity and are displayed in Figure 3.10. The only sensitivity issues mentioned were with regards to pulse identification (n=28) and physical examination by using percussion to feel organs (n=2). Issues with dextrous tasks included equipment slipping from contamination (n=4); tearing/sticking of gloves in cap lids (n=5); applying dressings (n=2); undoing small knots for evidence preservation (n=3); fine control, such as applying pressure with a scalpel (n=3) and others reported 'issues with dexterity in most tasks' (n=8). Although more issues were identified regarding dexterity, more respondents reported specific issues with sensitivity, all of which were respondents working in the clinical sector (n=30).

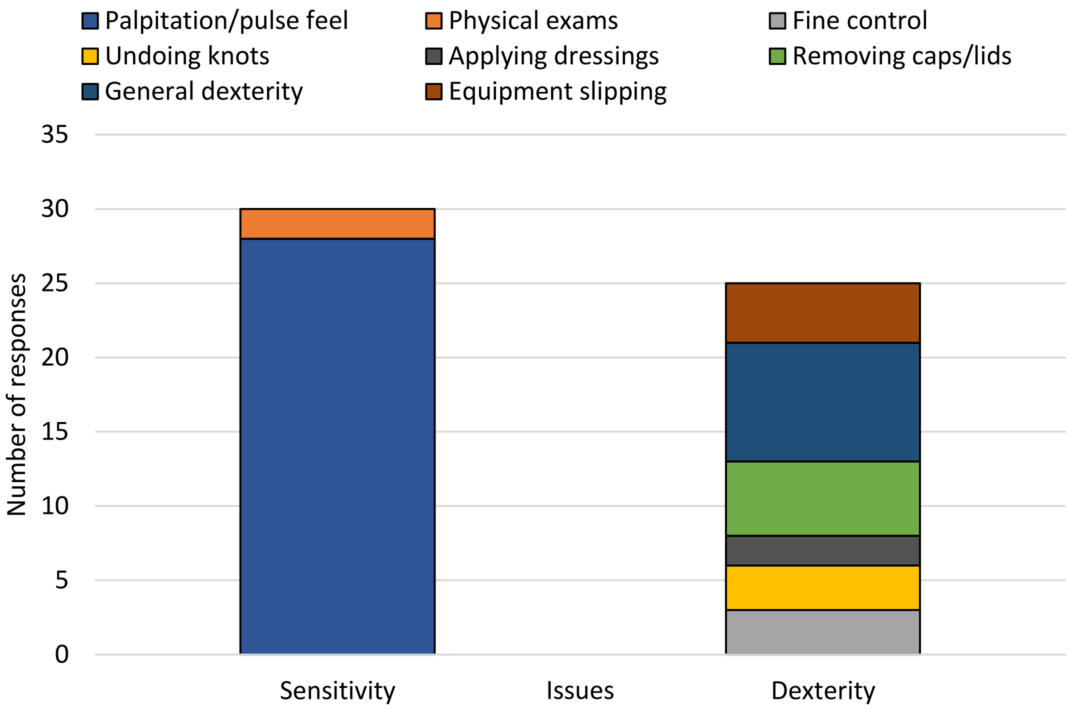


Figure 3.10. Breakdown of the responses regarding specific tasks affecting participants of the questionnaire. Tasks have been split into two sections to show the two main issues affected.

3.5 Discussion

The questionnaire shows that, although it is clear that NRL is still being used, the NBR gloves are more routinely worn. This is what is reported and predicted in line with the market trends (38). Three respondents stated that they used PVC gloves. All of which were in the medical field, dealing directly with patient healthcare. However, it is recommended by the National Health Service that vinyl gloves are not be worn where contact with bodily fluids is apparent due to their high failure rates (165). Thus, it is unclear whether these respondents are aware of which glove material they are using. The contaminants with which the gloves are in contact are mostly pertaining to bodily fluids, due the majority of the respondents working in the medical field (83%). These fluids are the fluids that would be expected to be in contact with gloves, the most common being blood, urine, and saliva. However, not previously considered, medical disinfectants also appeared as common contaminants. Regulations include that clinical staff maintain good environmental hygiene, thus cleaning around the patients/hospital/equipment is a vital part of their practice (22, 165). Furthermore, there are needs to come into contact with cleaning/disinfectants, when it comes to phlebotomy (inserting a needle to remove blood) (166, 167). These cleaners are normally alcohol-based wipes; thus gloves can be contaminated before proper use (168, 169).

NBR and NRL gloves are perceived to have similar issues; however, it is shown that NBR has more issues than the NRL glove. This could be due to the fact that only 39% of the respondents use NRL routinely, whereas 59% routinely use NBR. The largest issue for both gloves is around the sensitivity and ability to put on. Issues which were both highlighted in Mylon *et al.* (7), with the sensitivity issues being prevalent with 23% of the participants. In this study, only one issue was raised in the NBR that did not appear in the NRL, which was that the glove induced more sweat. The term 'sweatier' was used with the participants, thus it is thought that this means more sweat is generated when NBR is worn, in comparison to the NRL glove. Ability to put gloves on is a notably frequent issue with both gloves, which is an area which has seldom been explored in the literature (6, 9, 12). The only issue where NRL is more frequent than NBR is in the area of comfort. This could be due to a skin reaction to the NRL or from the material parameters (i.e. tighter on the skin). Mylon *et al.* (7) found contradictory issues, whereby more contact dermatitis was reported by the participants (5.9%) using the NBR gloves.

When the gloves are contaminated, the number of issues reported decreased by 6% for NRL and 12% for NBR. This is likely to be because the question was concerned about issues which were exacerbated by the presence of contaminants (i.e. not the issues that were already perceived to be present). Unsurprisingly, grip is the highest reported issue with both gloves, and dexterity/sensitivity is also reported to be affected. Comments were made on 'elasticity' being an issue after contamination, which could be due to the way these contaminants are reacting with the gloves, to either affect the stiffness of the material or elicit such a feeling. In addition, the ability to remove is noted as a more frequent issue when compared to the general issues with gloves asked previously. This is likely to be because it is harder to grab the glove due to the reported perception in reduced grip capability. It is unclear why fit would be an issue once gloves are contaminated. It is possible that the glove reaction to certain substances makes the user feel less comfortable, which respondents are perceiving as issues with fit (such as solvents making the glove feel tighter as they evaporate). It should be noted that 'fit' was not on the multiple-choice section for this and was typed in the 'other issues' section.

3.6 Questionnaire limitations

As with any questionnaire, there are several limitations with the results obtained from this study. Recollection bias is the most prominent issue in surveys. It is possible that some participants will not know which glove materials they are wearing but will have attempted to answer under the assumption of using a particular glove (i.e. participants could be using NBR but believe it is NRL). Also, if one particular glove has been worn for a long period of time, participants could, perhaps, think of issues that they believe may be associated with the other glove materials rather than reporting experienced issues. This has been highlighted in Mylon *et al.* (7) where participants reported the 'thicker feeling' gloves affected their tactility; however, the gloves were not measurably thicker. This may arise as a function of bias due to glove preference through use. As market trends lean towards other glove materials (such as the synthetic NBR over the NRL) there is a shift from hospitals purchasing habits, and more synthetic gloves are favoured from a business point of view (i.e. less incidences of allergies) (38, 165). However, as discussed in the Mylon *et al.* study (7) this leads to a bias in 'favoured' gloves. In essence, the people who wore NRL gloves for longer before the switch to NBR, show a preference for the NRL material. A way that this could have been mitigated was by asking if the gloves being used currently in their job role was their preferred glove choice, or part of an institutional decision of which gloves are being used. However, this study was pertaining to what gloves are used and the issues are perceived with these gloves, not about how users compare. Although it would be interesting to fully assess how glove users, who have had to change from their preferred glove materials, evaluate different gloves.

Although the contamination questions asked about any further issues, when providing answers, it is possible that participants filled out answers with the mind-set that the issues had not gone away, rather than them being further issues. For example, a respondent could have reported comfort as an issue for a NBR glove. Then when asked for further issues once the NBR glove had been contaminated, the participant responds with 'comfort' as the issue has not gone away, inducing a false positive for comfort being an issue when the glove is contaminated. Due to the nature of the questionnaire, multiple choice answers were provided with encouragement to include issues which were not stated in the answers provided. This box was utilised to add a wide range of substances for the section regarding which contaminants the gloves came into contact with. However, this was seldom used for the list of issues. Some of the participants used this box to comment on an issue that was already in the multiple-choice section or to put an issue which was already present (i.e. writing ‘glove ripping’ instead of clicking on ‘tearing’). This could cause the issues, whereby recollection bias makes the respondent think issues are present where none exist, just because they have seen the word in front of them (170, 171). Furthermore, common issues with the gloves could be undetected as participants do not have to think too deeply into their answers on an anonymised multiple-choice questionnaire. Another limitation is how the participants link the perceived issues together is also unobtainable from this study. This could be vital for perception of how glove users perform. For example, the largest issue in NBR is the loss of sensitivity (n=94) and the second largest issue is thickness (n=90). There is no indication in this questionnaire that the respondents believe that these two could be linked.

3.7 Conclusions

The findings from this chapter are:

- The most common examination gloves being used are composed of the NBR material, which participants appear to have more issues with than gloves composed of NRL. Although, this could be due to the NBR gloves being more widely used, hence more issues are noticed. It was shown, however, the more frequent issues being reported are similar for both of the materials.
- The most frequently reported issues are the loss of sensitivity, dexterity, grip, and ability to don. These issues, with the exception of donning ability, are reported to become further issues when both of these glove materials become contaminated.
- Comfort is also reported as a larger issue in NRL when compared to NBR, which could be down to the tightness of the gloves creating more sweat (although sweat was a reported issue in NBR and not NRL), being tighter or underlying allergies/sensitivity.
- Fit is more of a perceived issue with the NBR gloves, but an inherent issue throughout both glove types.

Overall, this questionnaire reveals the contaminants gloves come into contact with most frequently, as well as highlighting what effect glove materials may have on user performance. This allows for a greater depth of study into how glove behaviour is influenced by contamination. The issues surrounding donning and doffing the gloves are of great interest. Although the issues surrounding glove donning are relatively unexplored in the literature, there appears to be a problem amongst the general population of glove users.

Chapter Four: Donning and doffing

As previously discussed in Chapter 2, there is a lack of studies linking glove properties to donning capability and ease (6). To date, there is little literature regarding how the donning process is affected when moisture is introduced via either sweat or hand washing (172, 173). This was further identified as an issue from the questionnaire analysis in Chapter 3. It is referenced in the literature, and a selling point of many gloves, that the internal coatings e.g. polymer coatings (such as acrylics or hydrogels), or surface treatments help aid the donning of gloves (16, 57, 137, 174). The studies investigating the differences between coatings show that friction is reduced when hydrogels are used compared to chlorination (16, 57, 137, 174). However, beyond the fact that the friction is decreased, there is no evidence that this makes a glove 'easier' to don. In addition to this, there is an issue raised regarding the fit of gloves, and many people reported in the questionnaire (Chapter 3) that they were 'between sizes' and found gloves either too small or too large (172). Thus, assessing whether commercial gloves correlate to the hand sizes is required for assessing donning performance, as larger gloves are easier to don, but ill-fitting, which may affect performance (172, 173). This chapter concentrates on the inner glove interaction, that is, the donning side of the glove and the skin with different glove materials and treatments. The efficiency of donning and doffing gloves with different treatments, and with moisture present, is explored to mimic the conditions in which gloves are donned.

4.1 Introduction

Performing basic hand washing between glove use decreases the risks of infection between patients as the gloves could become damaged, contain pinholes, or break during use, leading to the hand being contaminated (175). However, the use of hand hygiene is considered unnecessary by some, and it has been shown that washing prior to and after glove use does not reduce pathogen transmissions (176). Nevertheless, it is still recommended that hands should be washed every time gloves are worn, especially given the covid19 pandemic where the use of PPE has increased and encouraged to be used where they would not have prior to the outbreak (31, 177, 178). A quick change of gloves is salient in high pressure environments, such as the medical field. The issues with donning gloves with wet hands are documented, as the glove sticks to the skin more and creates issues when trying to don gloves (7, 15, 119, 120, 179–181). Previous studies exploring force-donning relationships have shown that that wet hands require more force to don medical gloves (15, 119, 120, 179, 180). However, in the 'wet hands' condition, no drying took place, which is not representative of the conditions gloves are donned in The increase in force and sticking increases the time taken to put gloves on and/or leads to ill-fitting gloves with loose material in areas, and is regarded as unpleasant (181). Thus, assessing how the internal coatings and treatment of examination gloves could enable manufacturers investigate different coating requirements, and help purchasers/users make more informed choices regarding the selling point of gloves. Roberts and Brackley have previously assessed the coating applied to NRL surgical gloves, studying friction with skin and glass (57, 137). The work suggests longer chlorination time induces less friction, and hydrogel performs better due to an overall decrease in friction when compared to the chlorination. The wet condition was attained by applying water to the glove, rather than the finger. This could alter friction in two ways which are not replicable of the realistic donning scenario. Firstly, the coatings applied could affect the contact angle and the wetting of the surface, causing the moisture to spread. Secondly, the water-finger interaction should be present prior to hand insertion into the glove. Moisture in the hands has been shown to change morphology, which may induce changes in contact area (182). Furthermore, only one participant was used, and skin has been proven to have great variation between people, different interactions with moisture and thus, more people would have induced a greater variation in results. It is possible that the conclusions based on these results are erroneous and no statistical analysis was performed on any of the results. More recently Manhart, Hausberger, Maroh, *et al.* (174) looked at the tribological aspects of gloves with skin and compared porcine skin in an attempt to correlate human friction to an animal model. The study found that the skin had a good match with correlations between porcine and human skin friction. However, the human testing was only conducted once, whereas the porcine was tested 10 times. Although, similar conclusions were drawn to other friction studies, leading to the inference that gloves with polymer coatings are easier to don because there is less friction present (57, 137). No gloves, to date, compare the findings of internal glove coatings and their effects on the donning process and link this directly to the frictional properties of medical examination gloves.

4.2 Aim and scope

The aim of this study was to investigate the effects of donning different glove materials with dry and wet hand conditions, replicating in-situ donning scenarios. Wet skin has been shown to have higher friction coefficients when compared to dry skin (121, 183). This difference in friction can highlight the differences between glove treatments, coatings, materials, and the hand conditions, as well as informing better glove selection. These differences were determined by defining a protocol in which different gloves are assessed for how long they take to don and doff in dry and wet conditions. In conjunction with this, the frictional interactions between the skin and different internal glove coatings were assessed, with the aim of exploring correlations of medical glove friction to the time taken to don the glove.

4.3. Materials and Methods

4.3.1 Glove materials and characterisation

Glove Selection

Four types of commercially available medical examination gloves were used in this study. Chlorinated (cl) NRL (branded UltraCruz) and chlorinated NBR (branded Arco) were selected. These types of gloves are the most commonly used in industry due to the ease of access in the market, and they are relatively inexpensive (38). The intention of this study was to compare multiple glove coatings with the chlorinated treatment; however, the nature of the coatings is not determinable, as they are patented to the manufacturers and not disclosed on the packaging. Attempts were made to determine the coating via contacting the manufacturers, however no response was received. Thus, only one brand (Glove⁺) was used which had an internal polymer coating (PC) inside the NBR and NRL gloves. This led to a total of four gloves being used (Figure 4.1). Obtaining the roughness of each glove would be beneficial to the study, however due to the nature of the gloves, the surface roughness could not be obtained. This is because the surface roughness measurement instrument (Alicona) uses light to map the surface profile. In some cases, the material can reflect the light, which causes issues with the image. The materials used in this study were either too thin, or too reflective to obtain a detailed surface profile in which the average roughness could be determined.

Figure 4.1. Glove selection used in this study. From left to right; chlorinated NRL; polymer coated NRL; chlorinated NBR; and polymer coated NBR.

Thickness and size measurement

Glove thickness (T) was measured using a Mitutoyo micrometer (quick-mini, ± 0.01mm). Twenty samples of each glove type were measured at the location of the palm, middle finger, and fingertip. Each measurement was repeated three times in each area per glove. The Health and Safety Executive (HSE) recommends the measuring of hands across the palm, and the total length of the glove finger. Therefore, in order to assess if the gloves were of similar sizes, the same measurements were conducted on the gloves. Glove sizes were measured using a ruler in three areas, as shown in Figure 4.2. The areas measured were from:

- The distal middle finger to the knuckle
- The distal middle finger to the cuff
- The width across the palm

Where gloves were wrinkled/folded due to the packaging (as is visible in Figure 4.2), the glove was flattened as best as possible and held in place to ensure no folds/wrinkles were visible. However, some wrinkles may have contributed to differences in glove sizes. A total of 20 gloves were measured from each batch to get an average size for all three measurements.

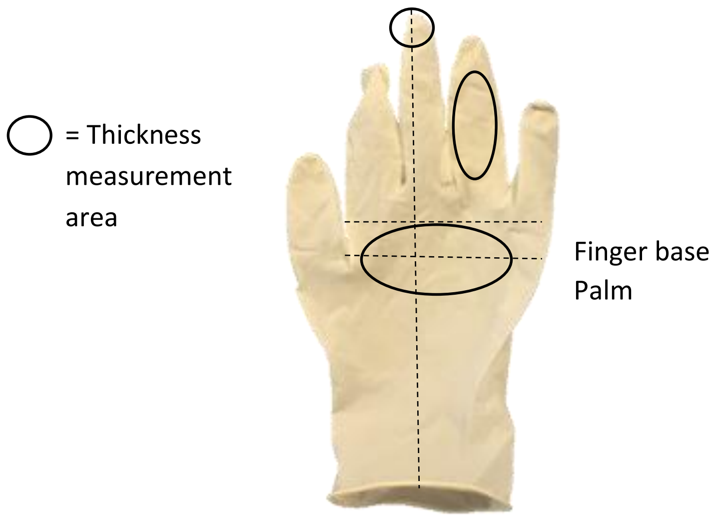


Figure 4.2. Depiction of areas of glove used for measurements.

Tensile strength

Gloves were tested as per EN regulations, using a tester Tinius Olsen TL-190 tensometer (Figure 4.3a) with a deflection rate of 500 (±2) mm/min. The EN 455-2 standards lay out the requirements of testing for physical properties (60). Standards state gloves should be cut to yield a 3 mm wide strip to be tested at 21°C (±2) with a humidity at 50% (±5) for physical properties. The glove was press cut around the palm area to yield a 9 cm long section, which had a 3 (±0.05) mm wide testing section, as in Figure 4.3b. The thickness along the 3mm wide strip was measured three times and averaged using a micrometer (Mitutoyo, C11XBS). The cut glove section was marked at an initial 2.5 cm spacing along the 3 mm strip. This was then loaded on the tensile tester and tested for the force at break (Fb), elongation at break (Eb), and tensile strength (Ts). Testing was carried out in a temperature and humidity-controlled room within the EN standards specification range, previously mentioned. Acceptable Quality Levels (AQL) requires gloves be checked to ensure they meet these standards. The standard practice is to test 2% of each batch of gloves, which should have no more than 1.5% of glove fail (61). If above 2.5%, the gloves are seen as low quality and the batch, as a whole, fails. For this study, as only a limited number of gloves were received, 12 repeats of these tests were conducted. Two sections were press-cut from each glove (around the palm area), thus only 6 gloves were tested (184).

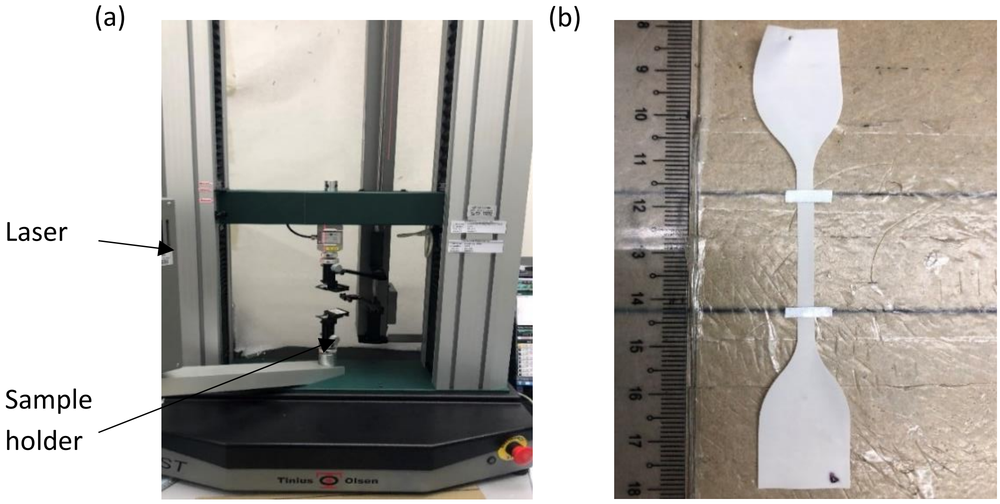


Figure 4.3. a) Tinius Olsen TL-190 tensometer and b) Press-cut sample for EN standard testing

The modulus of the gloves was also measured at 100, 300 and 500% strain, as per EN standards to produce stress-strain graphs for comparison of modulus. The stiffness (K) of the gloves was also calculated for discussion on how stiffness of the gloves could affect the donning process. The stiffness of each of the gloves was calculated using the stress at 100% strain using the following formula:

$$Stiffness\ (K) = \frac{stress\ (at\ 100\%\ Strain) \times Sample\ Width\ \times \mathrm{T}}{Inital\ sample\ length}$$

Equation 4.1

where T is the glove thickness (185). The stress at 100% strain was used as it is thought that stretching the glove beyond a 100% strain is unlikely. Stretching beyond this is an indication that the hand is not fitting into the glove correctly, due to incorrect sizing. This was noted in the video analysis of donning (discussed in section 4.4.2), whereby it was visually apparent that the gloves were not strained to over 100%. This is, however, unmeasured and a best estimate of the strain applied to the gloves when donning.

Contact angle goniometer

The wettability of a surface is measured through the contact angle (186). Contact angle measurements were carried out using a goniometer (ramé-hart, model 100-06, Figure 4.4) with a static sessile drop method. The gloves were placed onto the goniometer platform and 2 μl droplets of deionised (DI) water was syringed onto the sample surface, from a height of 0.8 mm. The droplet was analysed immediately after contact with the glove and was not left for a period of time.

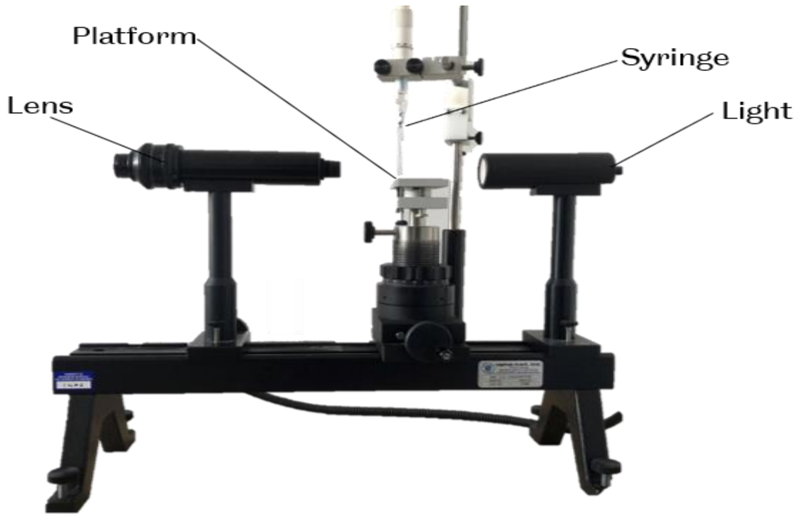
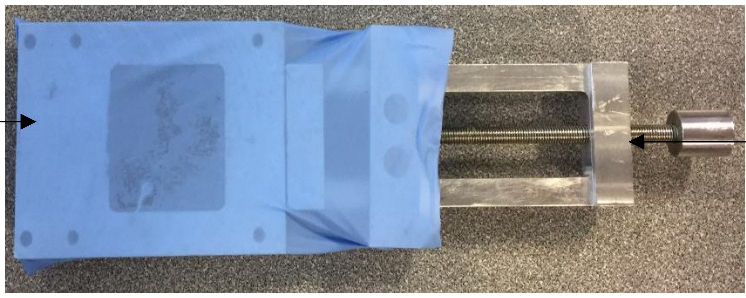


Figure 4.4. Schematic of goniometer. The syringe deposits a measured drop onto the substrate on the platform. This is then viewed via the viewing lens with sight aided by the light behind.

Strain

The gloves were tested for contact angles under strains of 0%, 25% and 50% to assess if strain affected the contact angle of the fluids (assessing donned/un-donned scenarios). The strain of the gloves was achieved using a stretching device, shown in Figure 4.5. This device is composed of two sections, a static section affixed to moveable section, which allows stretching of an attached glove. The glove sample was placed into the device and held with screws. All gloves were measured three times at each strain.

Glove sample clamped to device



Movable platform which stretches the clamped glove section

Figure 4.5. Stretching device with glove attached

4.3.2 Donning methodology

Three video cameras were set up in a triangulated position in order to capture all areas of the hand as the glove was being donned and doffed. A schematic of this set-up is shown in Figure 4.6. Prior to the study taking place, participants were asked to ensure their hands were washed and thoroughly dried around 15 minutes prior to starting. No gloves were worn in this 15-minute period. This was to get the hands into a natural state of moisture and temperature, ensuring all participants had a similar environment for the 'dry' condition. Gloves were placed side by side on a stool in front of the participants, who were then signalled verbally to proceed donning the gloves. Once participants had donned the gloves, they were asked to hold their hands out palms down to signal they had completed donning. They were then asked to doff the gloves and then hold out their hands once again, to signal that they had finished the process. To measure the donning efficiency with wet hands, participants were asked to wash their hands with liquid soap and warm water from the taps within the laboratory, and then partially dry, by patting with paper towel, using only two sheets of paper towel. Some remnants of moisture were still visible on the surface of the skin. The participants were then asked to don and doff the gloves in the same manner as before. This was repeated for all four types of gloves, in both wet and dry conditions in a forced randomised fashion, whereby the random pattern was checked over and changed to avoid a particular glove type always being in a particular position. In an attempt to double blind the experiment, both the participants and the principal researcher were blinded to which gloves were being used. The gloves were numbered 1-4 and placed into separate bags by a separate party. Thus, it was unknown which glove belonged to which brand until the end of the study, an approach suggested by Watson *et al.* (151). However, the gloves are distinct colours with NBR being blue and NRL being white/beige, thus the particular glove material was identifiable when watching the video footage. Nevertheless, the inner coating was not determinable by the colour without prior knowledge.

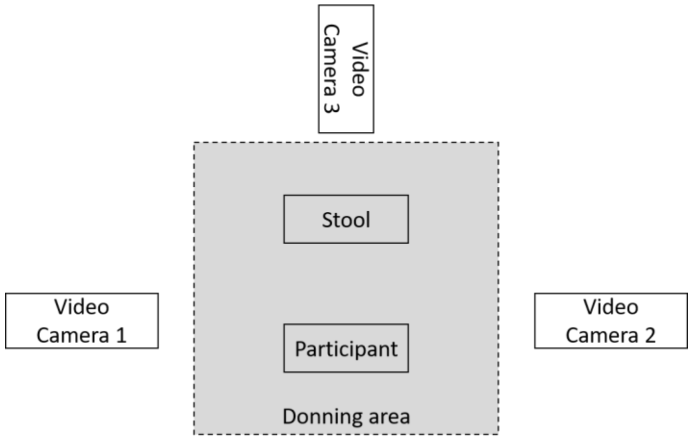


Figure 4.6. Schematic of the equipment set-up for capturing the donning and doffing process.

Participants

Participants were recruited from a forensic drug analysis laboratory (SOCOTEC, Burton-on-Trent, UK) where the analysis took place. These participants routinely don gloves, using on average 10-15 pairs of gloves per day. A total of 14 participants took part in the study, seven of which were male, and seven were female. The ages of the participants ranged between 22-40 and had all consented to being recorded and had no known allergies to NRL. It was determined that measuring the glove size and matching that to the HSE recommended size would not be representative of what occurs when gloves are selected. Consequently, all participants were given the option of selecting the size of gloves based on their own perception of what was 'best-fit'. That is, the participants selected the glove size based on the fit they were used to routinely. Participants hands were measured, using a tape measure, for the length (from the tip of the middle finger to the wrist), width (across the top of the palm), and circumference (measuring around the palm) by adapting a procedure used in Jee and Yun (187). Ethical approval was obtained from the University of Sheffield Department of Mechanical Engineering (No: 022731).

4.3.3 Questionnaire

As the participants in this study were experienced glove users, it was thought best to get their perceptions of the donnability and doffability of the gloves. This questionnaire was conducted for two reasons, to correlate perception with the results, and to assess preference correlation to results. The latter arising due to previous focus studies concluding that preferred glove types are seen to have better performance (7). As gloves and hand size were measured to assess whether the glove being donned was appropriate, the participants were also asked about the fit of the gloves (did the glove fit well?). To simplify, the questions asked were short, to the point and required a 'yes' or 'no' answer. This was asked after each test was conducted. The questions were as follows:

- Did the gloves fit well?
- Were the gloves easy to don?
- Were the gloves easy to doff?

4.3.4 Friction

Friction measurements

The friction between the skin and the gloves was measured for the same two hand moisture conditions used when assessing the donning. A multiaxial force plate (AMTI) was used (15cm × 15cm) to measure the friction between the skin and each glove. The force plate measures the force applied (Z) and the frictional force in both directions of the plate: side-to-side frictional force (y) and forward-backward frictional force (x), as shown in Figure 4.7. The force measured in the opposite direction of the sliding is the 'frictional force' (the force opposing the movement), whereas the force applied is the 'normal force' which is the vertical force utilized by the user pressing their finger down onto the plate.

(a) (b)

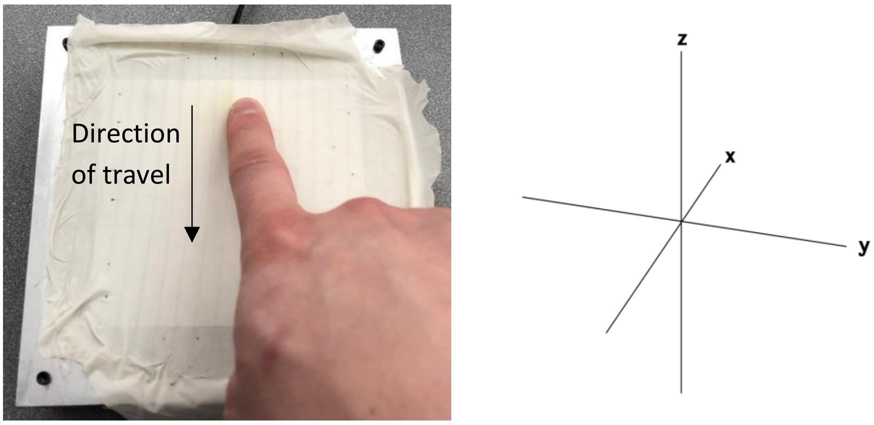


Figure 4.7. a) AMTI plate with glove attached, arrow shows the direction of finger travel, and b) the direction of forces with the *z* force as the normal load, the *y* force is the lateral (sideways) force across the plate and *x* is the force of the direction of the finger being dragged along the glove.

Friction Methodology

Each glove was cut open and fastened to the force plate using double sided tape to secure the glove completely to the plate, ensuring no relative movement, as in Figure 4.7. The exposed glove surface was the inner 'donning' side. To assess the frictional interaction between the finger pad and the gloves, the angle between the finger and the surface was kept at around 40^{o} and the finger pad was dragged along the plate, inducing a sliding action. Attempts were made with the palm of the hand, but the force plate was not large enough, and it was thought that the glove is rarely in contact with the whole hand during the donning process, due to the gloves being pulled and stretched. Thus, only the index finger of the participants was used to assess friction as used in previous studies (90, 116). The index finger of each participant was placed onto the glove and held at the desired force for 2-3 seconds before sliding was initiated. Participants were instructed to drag their finger down the glove for around 8-10 seconds, which results in a sliding speed of around 1.2-1.5 cm/s. Participants repeated each test three times in each condition (wet and dry). Previous studies had participants wet their hands and then don gloves (15, 119, 120, 179, 180). However, hands would be dried more rigorously prior to donning. Therefore, in this study, the wet condition was achieved by dipping the finger (as friction is only being assessed with the finger) in warm water at 30-32 °C and then blotting with a paper towel to remove most surface water. This was to recreate the act of drying the skin after washing the hands in tap water (181, 188). However, some moisture was still visible on the finger surface, as with the glove donning assessments. Ethical approval was obtained from the University of Sheffield Department of Mechanical Engineering (No:022735).

Participants

Four participants were recruited for the friction analysis (2 males and 2 females, aged 25-34). The participants were not the same participants used in the donning analysis due to participant availability.

Load selection

Five loads were used to assess the frictional properties, these were 0.1, 0.25, 0.5, 0.75 and 1 N. These loads were selected based on the load ranges used in the literature looking at the friction between glove materials and skin (57, 137, 174). However, this study looked at multiple loads as an assessment of different areas of the skin-glove interaction. A force of 1 N is similative of gripping and holding, thus has been selected as the highest load (189). At the fingers, the force will be higher as they have most contact due to the hand being forced into the glove. The low loads in this study represent the interaction between the glove and the palm/back of the hand region/side of the palms, which tend to have the glove stretched over them with little contact, until the fingers reach the end of the gloves.

Moisture measurements

MoistSense (Moritex, USA) was used for moisture measurement in the outer layer of the skin known, as the stratum corneum (Figure 4.8) (190). Moisture measurements were taken on the centre of the index finger three times for each friction test conducted. The moisture measurements were only taken for the friction tests, to highlight the difference in moisture.

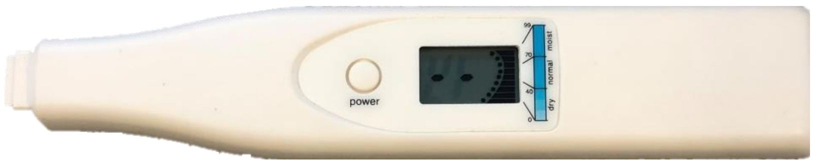


Figure 4.8. MoistSense used to measure the moisture in participant's skin.

4.3.5 Data Analysis

Friction analysis

As the donning procedure is a dynamic system (i.e. the hand and the glove move over each other in order to don the glove), dynamic friction has been measured. The dynamic friction has been calculated from a period where there is a plateau in the friction force, as shown in Figure 4.9, which shows an ideal graph with easily identifiable difference between the friction types.

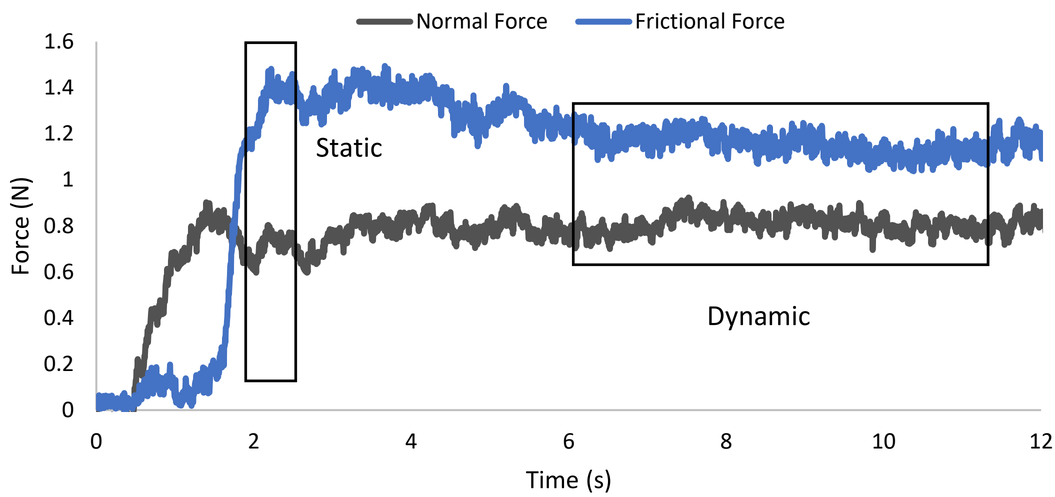


Figure 4.9. Typical graph for determination of friction coefficient. Dynamic CoF has been taken from the plateau in the normal force.

For analysis, the resultant horizontal friction force was calculated to account for any changes in local deformation (as the finger moves bulk-wise on the glove in the same direction) and for the misalignment of sliding (191). Resultant horizontal friction force was calculated using the equation:

$$Resultant\ friction\ force\ (N) = \sqrt[2]{x[N]^2 + y[N]^2}$$

Equation 4.2

where *x* is the friction force moving up and down the force plate, and *y* is the friction force moving side to side (Figure 4.7b). Coefficient of friction (CoF, μ) was then calculated via the equation:

$$\mu = \frac{\text{Resultant friction force (N)}}{\text{Normal force (N)}}$$

Equation 4.3

Power law relationships between the skin and glove friction have been previously reported in literature (90, 103, 107). Power fit laws have been applied to the data to obtain the best-fit lines for the trends using the formula:

$$Power\ Law\ Friction\ Force = a + bN^{n}$$

Equation 4.4

where *a and b are constants determined by the data, N* is the normal force, and *n* is the exponent determined by the data set.

Statistical analysis

The Shapiro-Wilk test for normality was used to assess the data for normal distribution (192). Data which was found to be normally distributed was analysed using one-way analysis of variance (ANOVA). This test looks to see if there are significant differences between all data sets (193). If significance was determined by the ANOVA test, a further post-hoc Tukey's Honestly Significant Difference (HSD) was conducted (194). If the data was found to be non-parametric, significance was tested for via the Kruskal-Wallis method (195). The non-parametric post hoc test chosen for this is the commonly used Dunn's Multiple Comparison Test (195). Statistical differences between the dry and wet conditions for each glove was assessed using a two tailed paired t-test (where parametric) or Wilcoxon Signed Ranks Test (where non-parametric) (196, 197). The significance level for the data being significantly different is set at $\alpha=0.05$. Thus, probability values (p), which indicate the significance of the test, must be <.05 in order to be defined as statistically significantly different.

4.4 Results

4.4.1 Glove properties

The average glove thicknesses at each measured location are shown in Table 4.1, along with the average thickness. It was found that the gloves have a tendency be thicker at the fingers than the palm. The gloves have a similar thickness overall, with the exception of the chlorinated NBR, which is just over half of the thickness of the polymer coated NBR gloves, on average.

Table 4.1. Gloves used and thickness measurement.

Glove ID	Treatment	Average Thickness (mm)			
		Palm	Finger	Fingertip	Average
Cl NBR	Chlorinated	0.06 (±0.006)	0.06 (±0.003)	0.08 (±0.005)	0.07 (±0.005)
PC NBR	Polymer	0.10 (±0.011)	0.13 (±0.006)	0.15 (±0.006)	0.13 (±0.007)
Cl NRL	Chlorinated	0.09 (±0.010)	0.12 (±0.005)	0.12 (±0.006)	0.11 (±0.008)
PC NRL	Polymer	0.10 (±0.012)	0.11 (±0.006)	0.13 (±0.007)	0.12 (±0.008)

± denotes standard deviation. Cl = Chlorinated, PC = Polymer coated

Physical properties

The gloves show differences in the break force, tensile strength, and elongation at break. It would appear that the greatest tensile strength is present in the PC NBR (33.40 MPa), which also has a large elongation at break (516%), as shown in Table 4.2. The greatest differences in the gloves are exhibited with the elongation at break. The NRL, when chlorinated, was shown to have the highest elongation at break (846%), whereas the least was the NRL when polymer coated (275%).

Table 4.2. Measured physical properties of gloves.

Glove	Fb (N)	Ts (MPa)	Eb (%)	K (N/mm)
Cl NBR	6.25 (±0.68)	25.77 (±5.26)	442.00 (±79.38)	0.022 (±0.002)
PC NBR	9.53 (±1.69)	33.40 (±5.00)	516.42 (±47.05)	0.024 (±0.002)
Cl NRL	8.62 (±0.60)	23.20 (±1.59)	846.08 (±77.28)	0.009 (±0.002)
PC NRL	7.53 (±0.50)	22.73 (±1.47)	275.92 (±142.39)	0.012 (±0.001)

± denotes standard deviation

Contact angles

The results obtained from the contact angles over the strain range showed similar results between strains for each glove type, with no statistically significant differences following ANOVA (Cl NBR $F(2,6)=1.036$, $p=.411$; PC NBR $F(2,6)=0.087$, $p=.918$; Cl NRL $F(2,6)=0.116$, $p=.892$; PC NRL $F(2,6)=0.124$, $p=.886$). This indicates that there is no difference in the contact angle of water when the gloves are strained. Thus, the results were collated, and are shown in Figure 4.10, as an average of the 9 measurements. The contact angles of the NBR show a good surface wettability, shown with contact angles less than 90°. This shows that the NBR material has a hydrophilic nature. The paired t-test shows no differences in the contact angles between the two NBR gloves (*t(8)=-0.029, p=.977*), with the contact angle for chlorinated averaging at 43.78° (±8.63) and the polymer coated glove averaging at 43.89° (±7.77). The NRL materials, on the other hand, is shown to have a hydrophobic nature, with contact angles greater than 90°. This shows poor surface wettability across both coatings. There are slight differences with the polymer coating having a slightly higher contact angle (121.78° ±5.25) when compared to the chlorinated glove (121.78° ±5.74). However, the contact angles are not found to be significantly different following a paired t-test (t(*8)=*-1.612, *p=.212*).

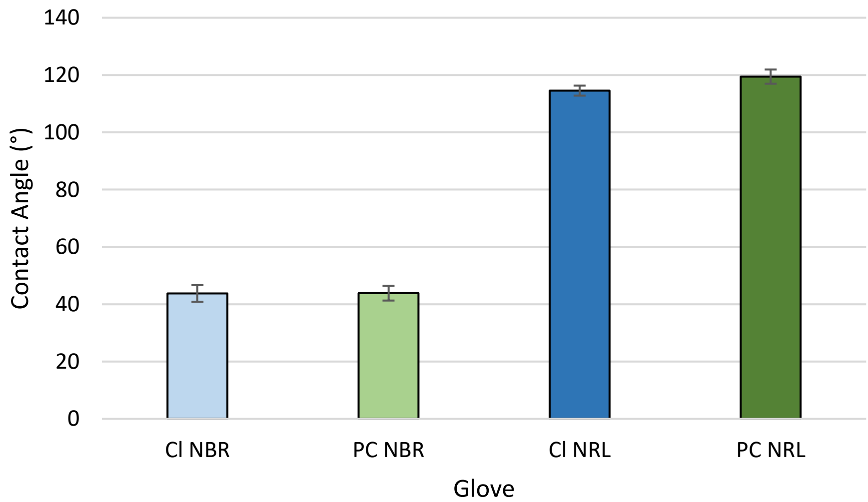


Figure 4.10. Contact angles of DI water on the inside of each glove. Error bars indicate standard error.

4.4.2 Glove size and fit

Glove size

The results from the measured glove sizes are displayed in Table 4.3. As only medium and large gloves were used in this study, only those have been measured and included here.

Table 4.3. Measurements of gloves used in this study.

Glove Type	Glove length (cm)		Finger to Knuckle (cm)		Palm width (cm)	
	M	L	M	L	M	L
CL NBR	24.7 ($\pm$0.18)	26.3 ($\pm$0.12)	8.1 ($\pm$0.10)	9.0 ($\pm$0.23)	9.2 ($\pm$0.08)	9.4 ($\pm$0.25)
PC NBR	24.2 ($\pm$0.21)	25.9 ($\pm$0.15)	7.6 ($\pm$0.19)	7.9 ($\pm$0.15)	9.2 ($\pm$0.03)	10.2 ($\pm$0.21)
Cl NRL	24.8 ($\pm$0.25)	24.9 ($\pm$0.18)	7.8 ($\pm$0.12)	8.3 ($\pm$0.11)	9.3 ($\pm$0.21)	9.7 ($\pm$0.31)
PC NRL	25.3 ($\pm$0.12)	25.3 ($\pm$0.17)	8.0 ($\pm$0.18)	8.3 ($\pm$0.16)	9.5 ($\pm$0.18)	10.2 ($\pm$0.20)
Average	24.75 ($\pm$0.45)	25.60 ($\pm$0.62)	7.88 ($\pm$0.22)	8.38 ($\pm$0.46)	9.30 ($\pm$0.14)	9.88 ($\pm$0.39)

$\pm$ denotes standard deviation

Glove fit

The participants perceived best-fit of gloves were compared against the HSE recommended size in Table 4.4. There was one participant who had a recommended size which matches their perceived best fit, and one participant wore gloves that were a size smaller than that recommended, based on the sizing of their hands. The remaining 12 participants had a preference to wear gloves that were larger than recommended based on their finger and/or palm size.

Table 4.4. Comparison of perceived best fit gloves used by participants to HSE glove size recommendations from hand sizing (149).

Perceived best fit size	HSE recommended size	
	Finger	Palm
M	S	S
L	S	M
M	M	M
L	L	M
M	M	S
M	S	S
M	S	S
M	S	S
M	S	M
M	S	M
L	L	XL
L	M	L
M	S	S
M	S	S

S = Small, M = Medium, L = Large and XL = Extra Large.

4.4.3 Donning and doffing

Donning steps

Upon analysing the videos, it was noticed there were four key steps to donning a glove. The first step is picking up the glove(s). Participants were instructed to don and doff the gloves in the manner they normally would and reminded that this was not competitive. Nevertheless, it is viewed that the time taken to pick up the glove does not affect the key donning action, as picking up the glove does not affect the act of donning. Thus, for the purpose of this study, the time taken to pick up the gloves has been removed for analyses. The remaining three steps consist of the following:

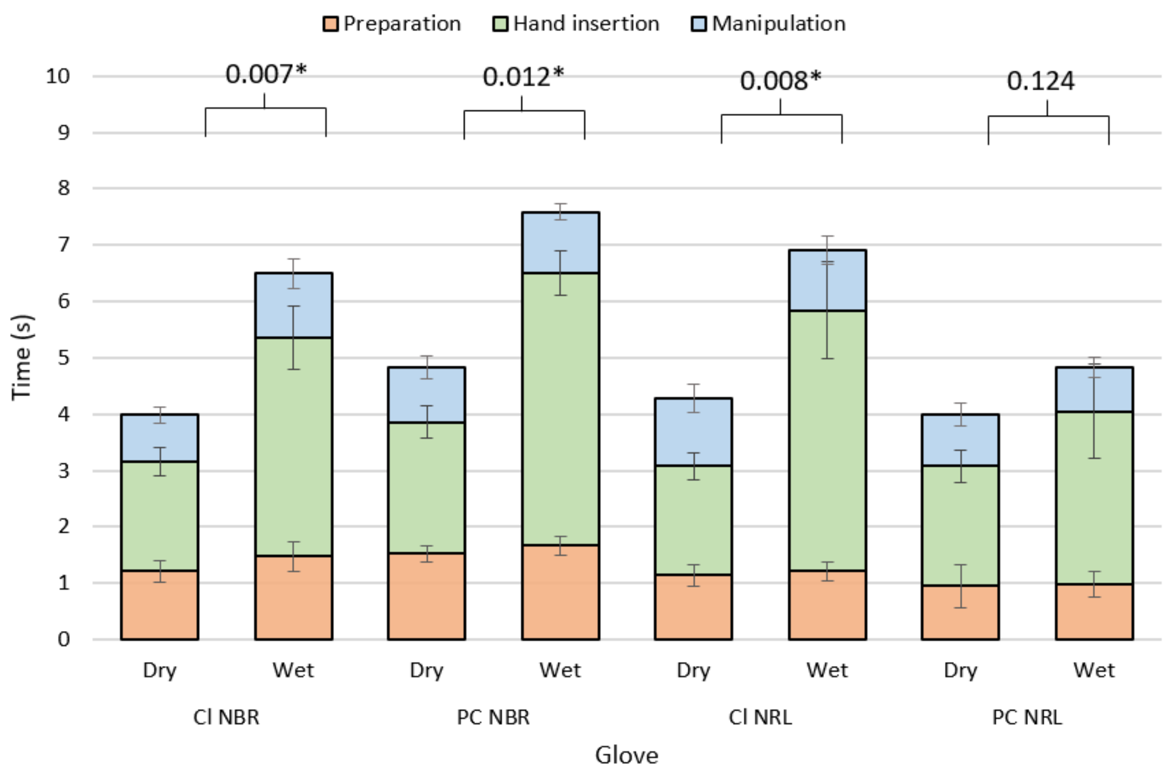
- **Preparation:** This is the time taken to orient and mechanically separate the glove whilst preparing to insert the hand (Figure 4.11a).
- **Hand insertion:** This is the time taken for the fingers to reach the end of the fingertips of the glove (i.e. the hand is fully inserted into the glove) (Figure 4.11b).
- **Material pulling/Glove manipulation**: This is the total time taken to manipulate the glove after hand insertion. These actions consisted mostly of manipulating the cuff/unrolling the cuff and pulling the glove to ensure fit (Figure 4.11c).

(a) (b) (c)

Figure 4.11. Glove donning steps. (a) shows the preparation step, opening the glove, (b) shows the hand insertion step and (c) shows the pulling of material down the fingers to comfortably fit hands.

Donning

In all cases, there were no large differences between the left and right hands. Thus, the time taken to don a glove has been averaged, and the results presented show the time taken to don one glove only. Figure 4.12 shows the average of the results obtained, broken down into the three stages of donning in both the dry and wet hand conditions. The results show that chlorinated NBR and polymer coated NRL were the quickest to don overall when the hands were dry, taking 3.99 *(±1.18)* seconds and 4.00 *(±1.71)* seconds, respectively. When the hands were wet, the gloves took longer to don, and there were more visible issues with the gloves, such as sticking to the fingers. Paired t-tests show that the differences between the time taken to don the gloves in both hand conditions was statistically significant for the chlorinated NBR and NRL, as well as the PC NBR ($p<.05$, Appendix B1). The polymer coated NRL gloves were the quickest to don when wet (4.83 *(±2.74)* seconds), and there is no significant difference between the dry and wet conditions ($t(13)=2.160$, $p=.124$). Table 4.5 shows the results from conducting ANOVA on all gloves, in both conditions. No significant differences were observed between any of the gloves at any of the three stages in the both the dry and wet conditions ($p>.05$). Differences were, however, found in the total time taken to don the gloves in the dry condition ($F(3,52)=-4.283$, $p=.009$). Tukey's (HSD) tests were further conducted on the total time in the dry condition, which showed statistically significant differences between Cl NBR and PC NBR ($Q=4.130$, $p=.026$) as well as PC NRL and PC NRL ($Q=4.552$, $p=.012$). The results of these tests are shown in Table 4.6. Paired t-tests on the dry and wet conditions for each glove reveal that the largest differences are present in the 'hand insertion' step, as the time taken was significantly increased for each glove ($p<.05$. Table 4.7).



** Indicates statistical significance (p<.05)*

Figure 4.12. Average times taken to don the medical gloves broken down into the three key tasks. Error bars denote standard error.

Table 4.5. Results of ANOVA/Kruskal-Wallis test conducted across the total donning time, and each step of the donning process in both dry and wet conditions.

Donning stage	***Result***	
	Dry	**Wet**
Total	*F(3,52)=4.283, p=.009**	*F(3,52)=1.876, p=.176*
Preparation	*F(3,52)3.399, p=.101*	*F(3,52)=3.992, p=.054*
Hand insertion	*F(3,52)=1.907, p=.340*	*H(3,52)=0.289, p=.529* [A]
Manipulation	*H(3,52)=3.191, p=.717* [A]	*F(3,52)=1.122, p=.329*

** Indicates statistical significance (p<.05).* [A] *Denotes the use of Kruskal-Wallis test due to non-parametric distribution of data.*

Table 4.6. Post Hoc Tukey's test results conducted on the total time in the dry condition (ANOVA= .009).

		Glove		
		PC NBR	**Cl NRL**	**PC NRL**
Glove	**Cl NBR**	*Q=4.130 p=.026**	*Q=0.721 p=.900*	*Q=0.4219 p=.900*
	PC NBR		*Q=1.142 p=.086*	*Q=4.552 p=.012**
	Cl NRL			*Q=3.410 p=.834*

** Indicates statistical significance (p<.05).*

Table 4.7. Results of paired t-tests comparing dry to wet in all glove types at each step of the donning process.

Donning stage	**Glove**			
	Cl NBR	**PC NBR**	**Cl NRL**	**PC NRL**
Prep	*t(13)=-1.224 p=.183*	*t(13)=-0.354 p=.682*	*t(13)=-0.387 p=.647*	*t(13)=-0.209 p=.884*
Hand insertion	*W(13)=8 p=.013** [A]	*W(13)=5 p=.013** [A]	*W(13)=5 p=.002** [A]	*W(13)=10 p=.002**
Manipulation	*t(13)=-1.537 p=.118*	*W(13)=5 p=.083* [A]	*t(13)=-0.424 p=.577*	*W(13)=35 p=.395* [A]

** Indicates statistical significance (p<.05).* [A] *Denotes the use of Wilcoxon-signed ranks test due to non-normal distribution of data.*

Doffing

Figure 4.13 shows that the time taken to doff the gloves had an average time range of 1.68-1.93 seconds across the eight conditions. When the hands were wet, there was a slight increase in the average time taken to remove the gloves, with the exception of PC NBR, where the time taken to remove decreased, on average (dry= 1.93s ±0.29; wet= 1.84s ±0.65). Paired t-tests show there are no significant differences between the any of the hand conditions (*p>.05*, appendix B2). ANOVA also reveal that there is no significant difference between all gloves in either the dry (*F(3,52)=1.250, p=.301*) or wet (*F(3,52)=0.011, p=.999*) conditions.

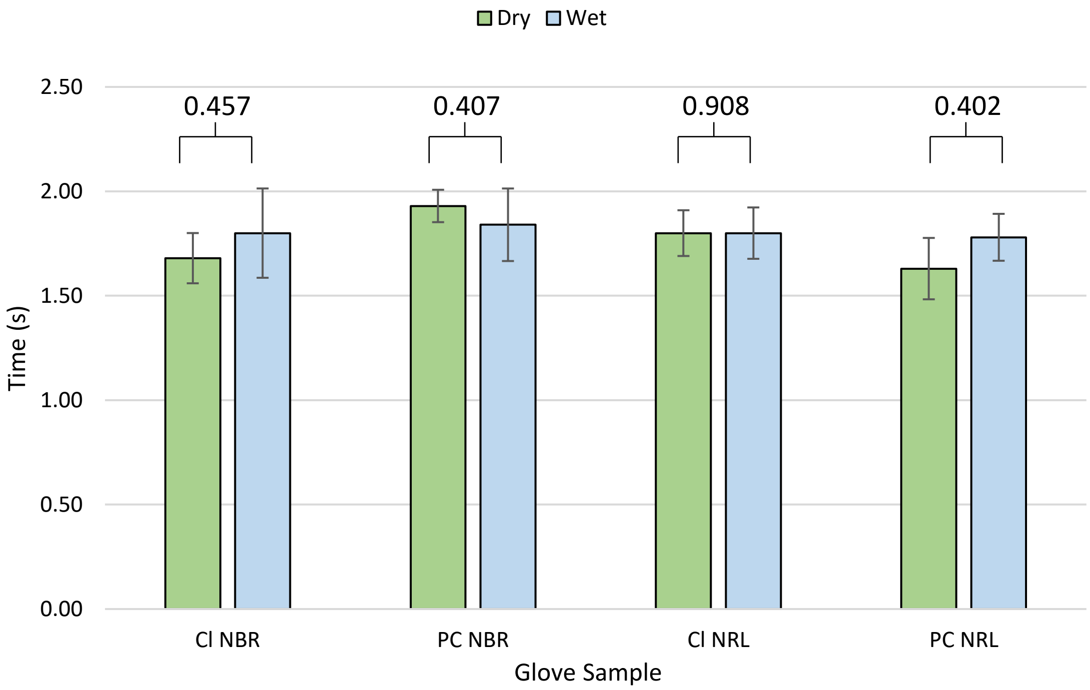


Figure 4.13. Average results of time taken to doff the medical gloves, with paired t-test (*p*-value) results between the two conditions Error bars denote standard error.

4.4.4 Gloves sticking incidence

As hands were placed into the glove, it was observed that on several occasions the gloves stuck to the fingers in localised areas, decreasing the efficiency of placing the glove on the hand. These incidences of sticking were noted down for each glove. A sticking incidence was noted when the glove was being pulled by the participant, but there was no movement of the overall glove. In some cases, these sticking incidences were quickly fixed by harder pulling of the gloves, which lasted around 0.1-0.2 seconds. In other cases, the gloves required total cessation of the pulling action, to manipulate the glove and pull the specific areas. A total of 329 incidences of sticking were noted across the 14 participants. Figure 4.14 shows the different hand locations where sticking was observed. This was formulated based on the common areas where the fingers became stuck to the hand. It is important to note, that only one finger may have been stuck in any of the locations. All locations have been labelled the same across the fingers for the sake of visual simplicity. In all the gloves, there was a greater frequency of sticking/high friction at the section at the top of the palm (location D) and the proximal location of the fingers (location C). The number of incidences of sticking increased in the wet condition, due to the increased moisture causing adhesion (Figure 4.15).

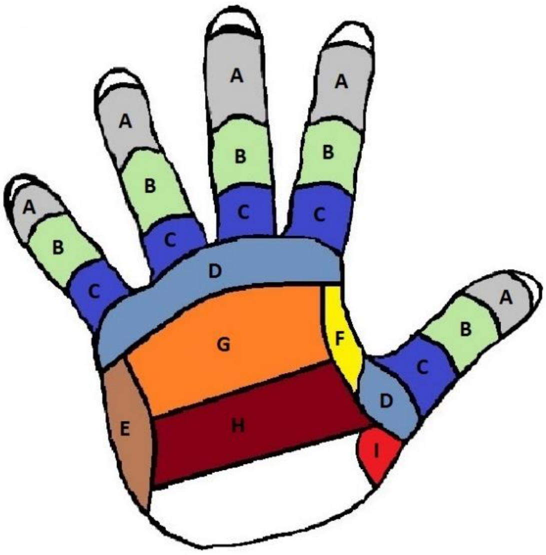


Figure 4.14. Map of the glove showing areas where sticking of the fingers/hand occurred on the glove throughout the study.

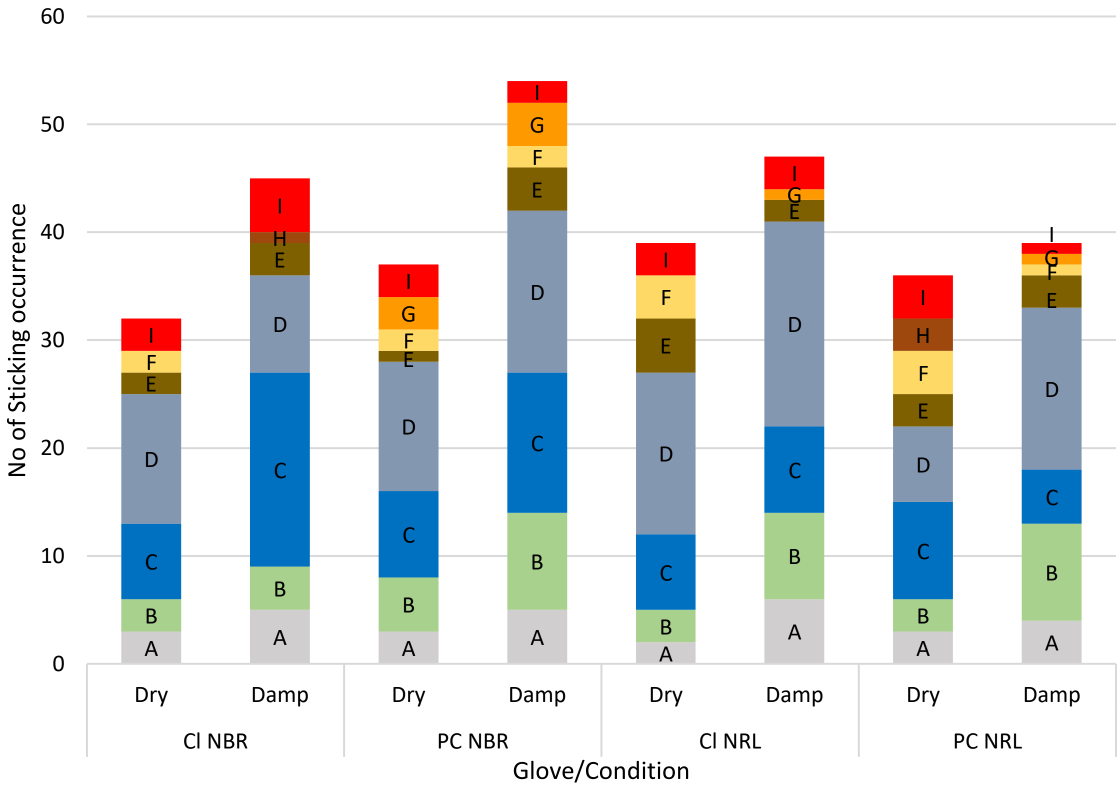


Figure 4.15. Incidences of sticking in the different areas within all of the gloves shown in Figure 4.14.

4.4.5 Perception of fit, donning and doffing

Results from the participant questions after donning/doffing the gloves are shown in Figure 4.16. The graph shows how many responded ‘yes’ to the questions asked. Chlorinated NRL has a good overall reported fit with 9 out of the 14 participants responding that the glove fit well. On the other hand, the polymer coated NRL gloves had the poorest reported fit with only 4 participants responding that the fit was good. When the hands are wet, the gloves were perceivably harder to don with only two respondents stating that both of the PC gloves were easy to don. However, the chlorinated gloves were perceived to be harder to don with only one participant stating that the chlorinated gloves were easy to don when the hands were wet. On the other hand, doffing the gloves had no significant impact on the user perception. The chlorinated NBR was perceived to be slightly less easy to don when the hands were wet. However, the polymer coated NRL was shown to increase from 12 people finding it easy to doff to 14 when the hands were wet.

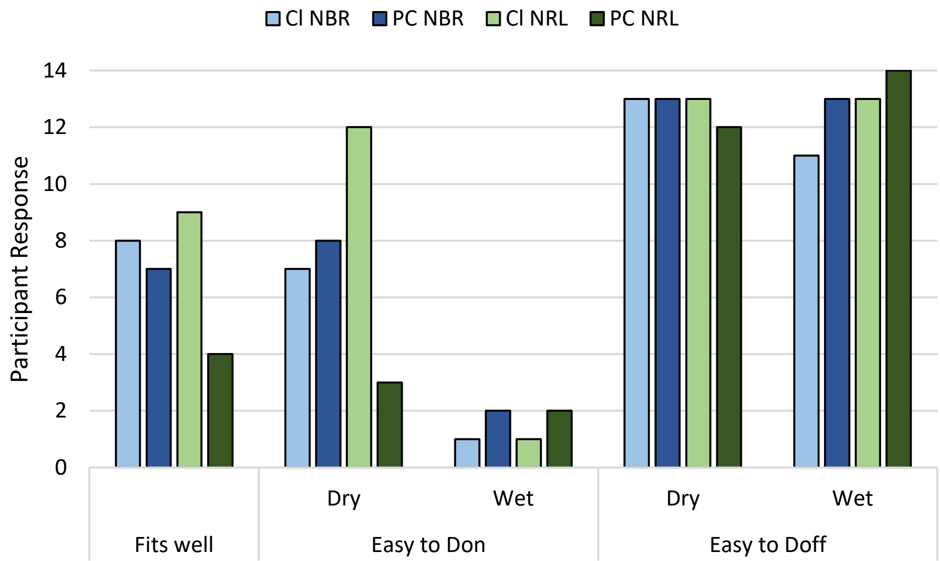


Figure 4.16. Responses of the participant questionnaire regarding the fitting of the gloves and the ease of donning and doffing.

4.4.6 Friction

Data has been processed and only graphs are shown in this section. All calculated CoFs for each load, complete with the statistical analysis conducted is included in the appendix (B3-B5).

Moisture

The readings produced from the MoistSense give a reading in Arbitrary Units (A.U). A reading of 0-40 means the skin is lacking in moisture and is dry. When between 40-70 the skin is at a healthy moisturised state, whilst a reading over 70 suggests the skin contains more moisture than the natural state. As participants had similar skin moisture results across each of the gloves, averages have displayed for each participant (Figure 4.17). The results were similar for each participant in the dry section, showing a healthy dry skin around 57-61 A.U. The wet skin moisture results were significantly higher in each participant (94-98 A.U) following paired t-tests (P1: $t(11)=22.411, p=<.01;$ P2: $t(11)=-24.740, p=<.01;$ P3: $t(11)=-61.660, p=<.01;$ P4: $t(11)=-53.334, p=<.01$).

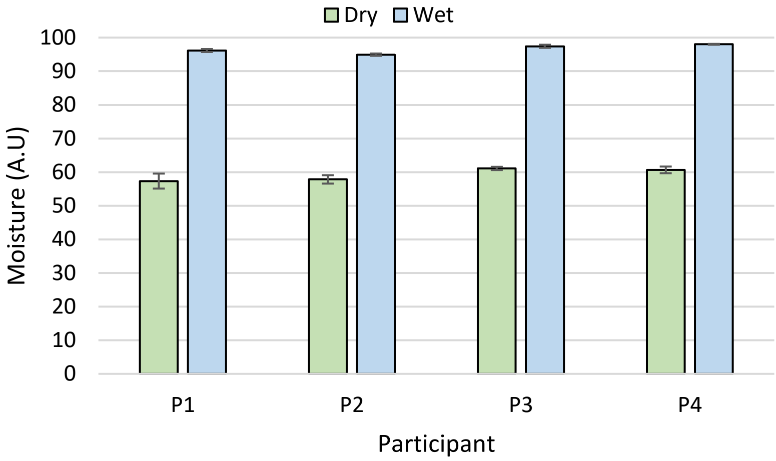
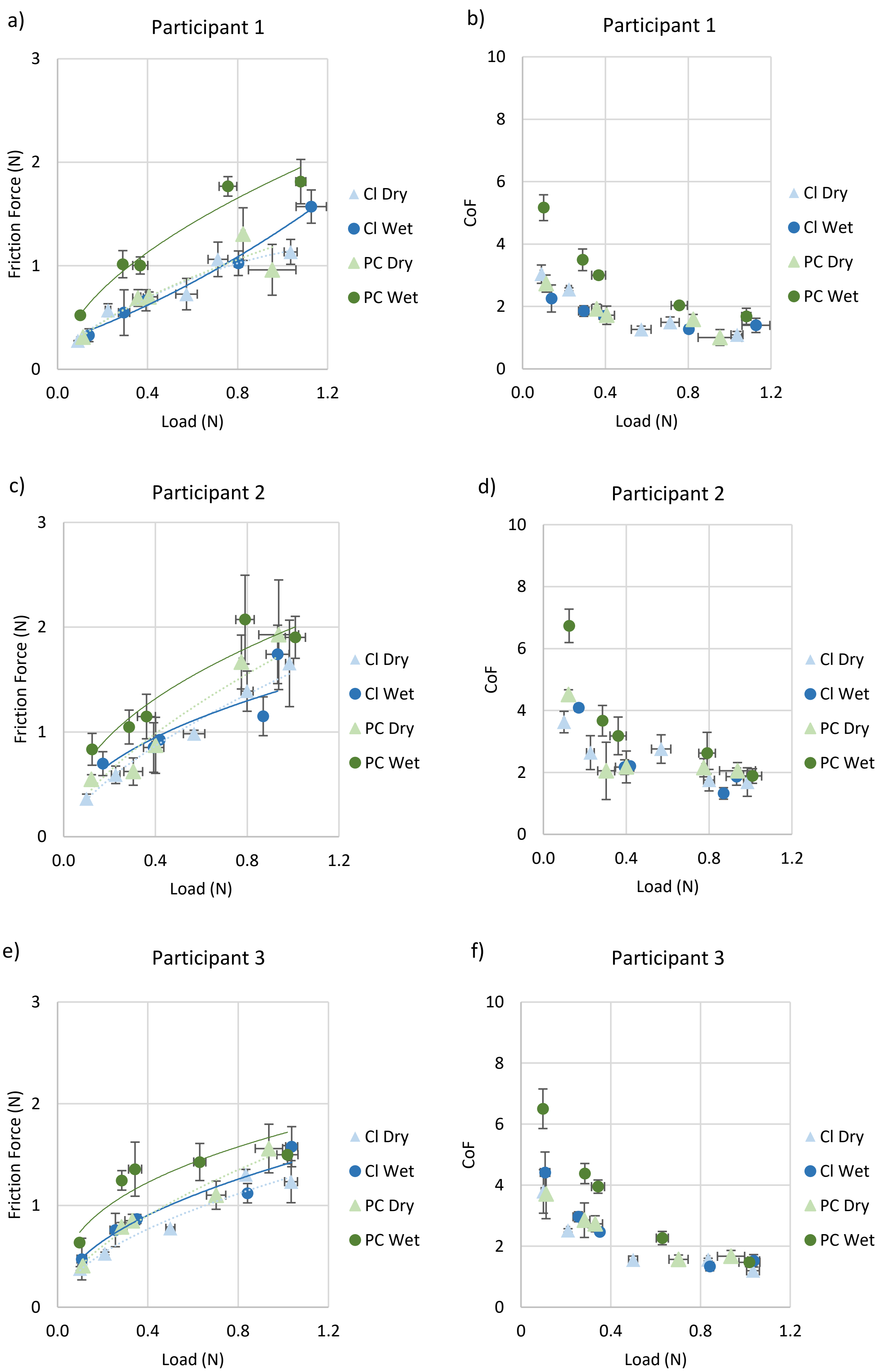
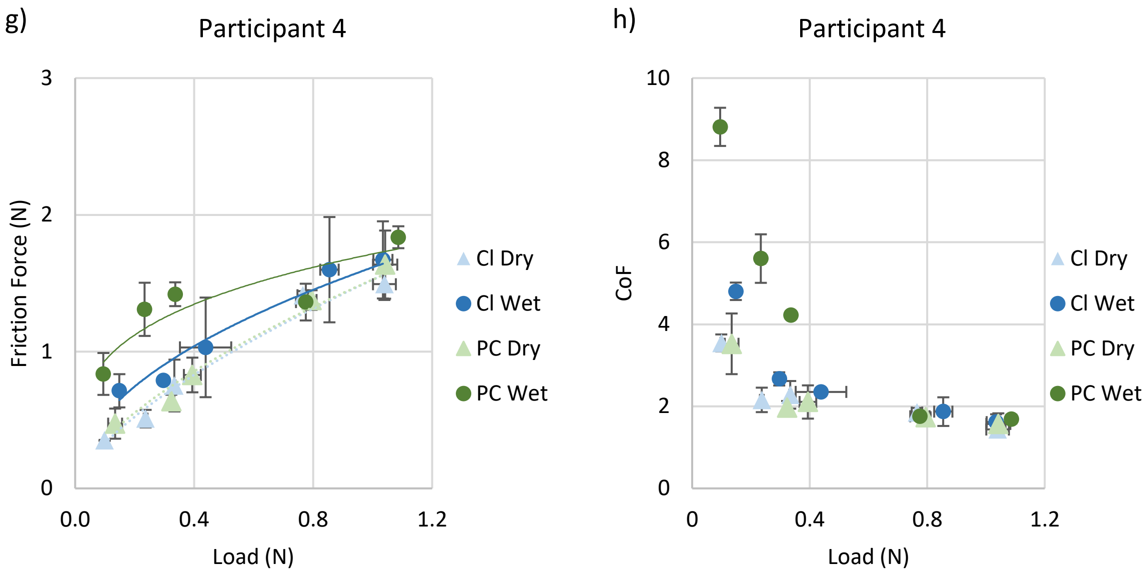


Figure 4.17. Average moisture per participant across the 4 gloves. Error bars denote standard error.

NBR friction

The results obtained from the friction between the skin and NBR are shown in Figures 4.18 (a-h). In all instances, the friction increases with increasing load, leading to a lower CoF as the load increases. It is clear from the data that the inclusion of moisture causes an increase in friction with both the polymer coated and the chlorinated gloves. Most significant differences between the wet and dry friction were noted in the polymer coated gloves ($p<.05$). The statistical analysis for these datasets is included in the appendix (B2-3). In the wet hand condition, there was little difference between friction observed between the chlorinated and polymer coated gloves, with very little statistical differences amongst the participants following paired t-tests across all loads ($p>.05$). However, significant differences were found between the friction of the two coatings in the dry condition ($p<.05$). The statistical analysis for these datasets is included in the appendix (B2). In the wet condition, more friction was present in the polymer coated, which is converse to what is expected to happen, as the polymer coating is said to reduce friction to enable a smoother donning process. At a low load when wet, the highest friction coefficients are observed between all participants (μ=5.17, 6.73, 6.50 and 8.81, respectively). In addition, stick-slip was identified in some participants in the polymer coated gloves. As the load increases, the CoFs become quite similar across the gloves, but chlorinated dry glove has a tendency of producing the lowest friction across the gloves, with CoFs ranging between 3.79 and 1.1.


a)
Participant 1
Friction Force (N)
Load (N)
b)
Participant 1
CoF
Load (N)
c)
Participant 2
Friction Force (N)
Load (N)
d)
Participant 2
CoF
Load (N)
e)
Participant 3
Friction Force (N)
Load (N)
f)
Participant 3
CoF
Load (N)
Cl Dry
Cl Wet
PC Dry
PC Wet



Figures 4.18 a-h. Average friction and the CoF of chlorinated and polymer coated NBR gloves across all participants. Error bars denote standard deviation.

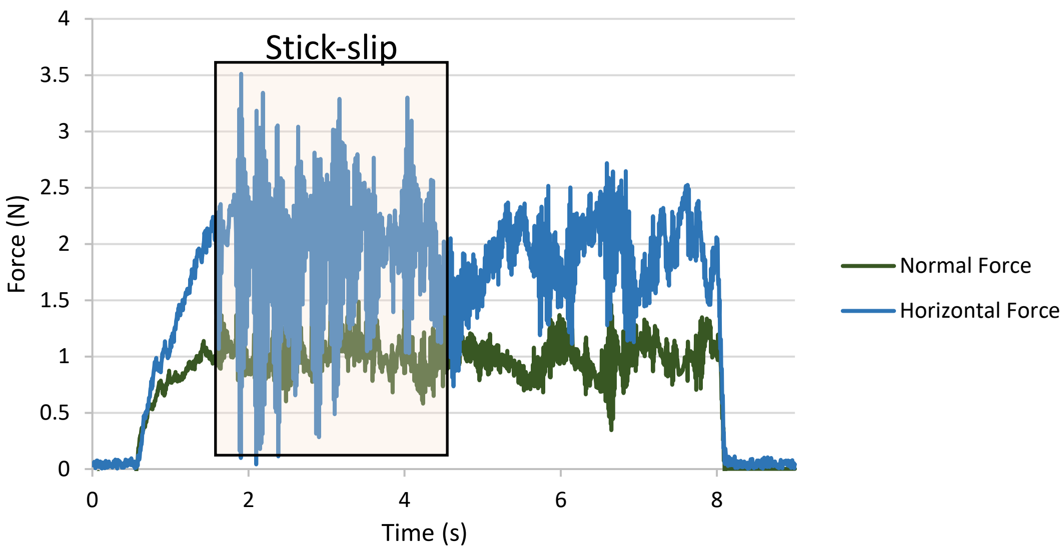
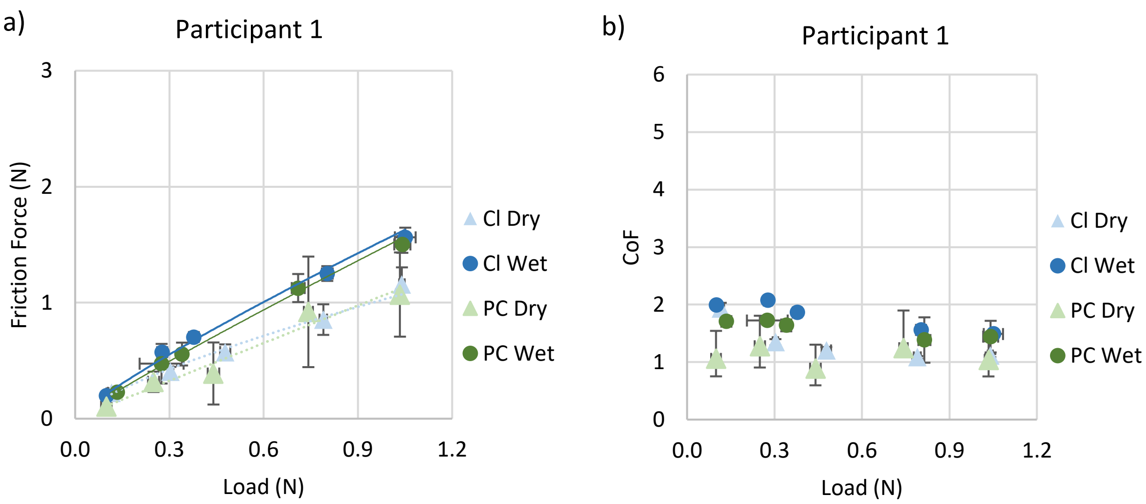
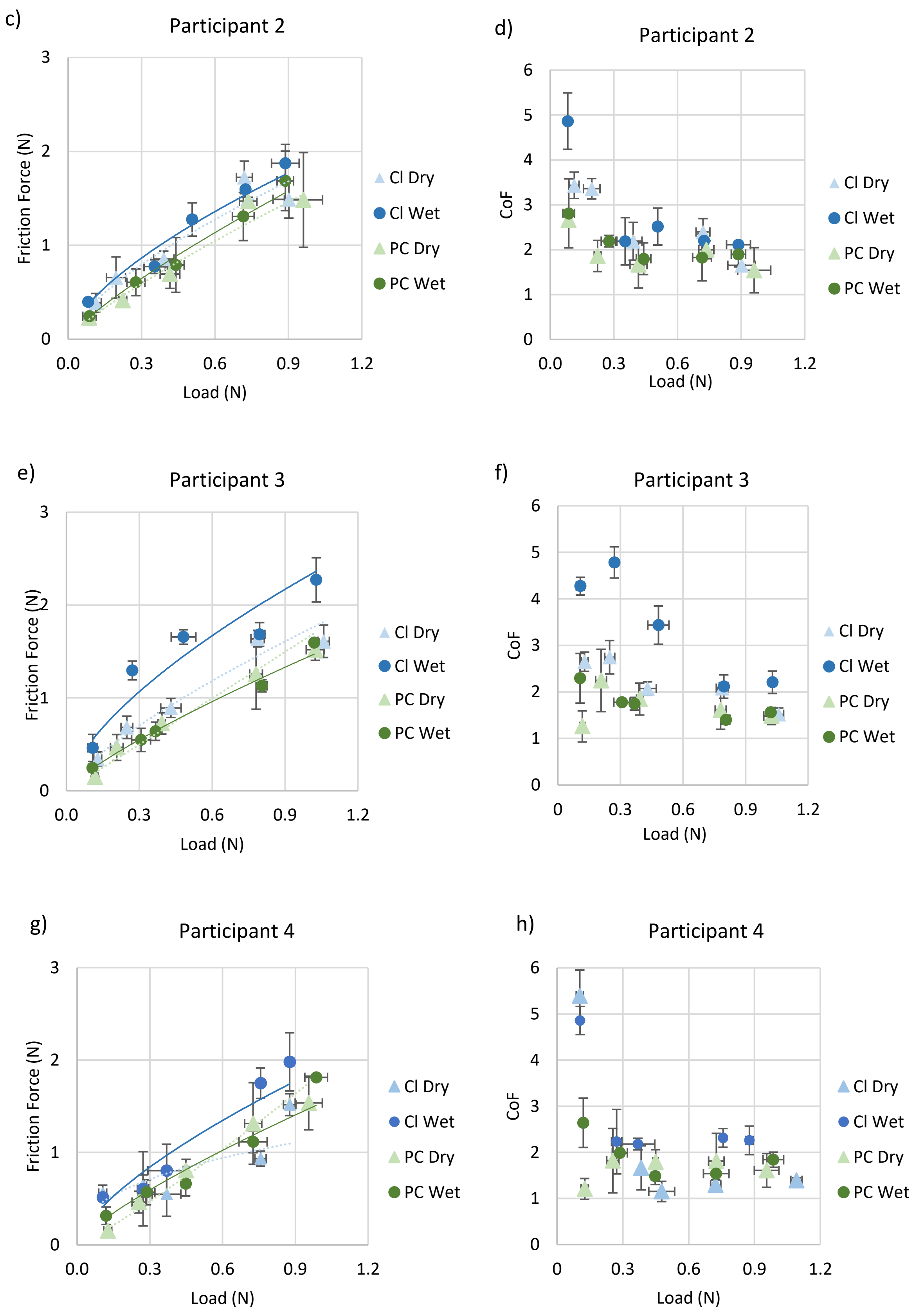


Figure 4.19. Example of the stick-slip induced by the rapid alternation between static and dynamic friction.

NRL friction

Figures 4.20 (a-h) show the friction forces and the CoFs of the skin-glove interactions with the NRL gloves. The NRL friction shows to have differing behaviours to the NBR, with the friction produced in both the wet and dry being generally lower than the friction produced in the NBR material. In most cases, CoFs between the skin and gloves increased upon the addition of moisture, with some statistically significant differences observable with the chlorinated glove samples. Full statistical tests are shown in the appendix (B4-5). With participant 1 there is very little fluctuation in CoF as the load increases. T-tests show little difference between the gloves in all participants (*p>.05*). However, across all participants in the wet condition, significant difference is noted between the polymer coated films and the chlorinated films in all participants at the lowest target load (*p<.05*), as noted with the NBR. In general, the friction of the polymer coated gloves is lower in the dry condition with the lowest CoF observed in the 0.5 N target load in participant 1 (μ=0.88). The increase of friction once moisture is introduced is minimal in the polymer coated gloves when compared to the chlorinated. For example, with participant 3, the polymer coated gloves show an average CoF difference of 0.06 between the wet and dry conditions at the highest target load (1 N). On the other hand, in the chlorinated gloves, there is a CoF difference of 0.66. No significant differences were found between the CoFs in the wet and dry conditions following paired t-tests (*p>.05*) however differences were noted in some of participants friction in the chlorinated samples. These significant differences were mostly observed at the higher loads (appendix B4). Stick-slip was also observed with the NRL gloves, however, this time participants had stick-slip observed in the chlorinated gloves, rather than the polymer coated as seen in the NBR.





Figures 4.20 a-h. Average friction and the CoF of chlorinated and polymer coated NRL gloves across all participants. Error bars denote standard deviation.

4.5. Discussion

4.5.1 Donning and friction

Of the gloves used in this study, it is shown that there is little difference between the time taken to don the different glove materials, with different coatings, when the hands are dry. The longest time was shown in the polymer coated NBR glove. It is evident from the results, that participants generally take longer to don the gloves when hands are wet. This reflects the issue of donning gloves with sweaty or wet hands from washing (15, 57, 120). The polymer coated NRL was the only glove type found to be unaffected by moisture changes, as indicated by the lack of a statistically significant difference between the two hand conditions

When broken down into the three key steps present within donning, statistically significant differences were found between the polymer coated NRL when compared to the other gloves in the wet hand condition. This further indicates that this glove was quicker to don than the other glove. Statistically significant differences were present mostly in the preparation stage when the hands are wet. This is likely to be due to participants not being able to grip and/or open the gloves as efficiently than with the dry hands. There are also large variations in the hand insertion step, due to the glove sticking to the skin or fingers getting stuck in the glove. There is a greater frequency of sticking/high friction at the section at the top of the palm (location D, Figure 4.14) and the first location of the fingers (location C, Figure 4.14). This could be due to a combination of the nature of glove packaging as well as the behaviour of the participants when donning the gloves. Medical gloves are normally compressed into boxes for packaging (14). In some cases, this causes the inner surface of the gloves to stick together, which are only separated by mechanical action prior to donning the glove or whilst the glove is being donned. Separating the glove to insert the hand takes time, and when the gloves are manipulated by the participants in the preparation stage, the participants tended to open the glove, either by rubbing or pulling the glove, at the palm or cuff only. The sticking and friction with the skin then occurs as the participant opens the finger holes using their fingers once the hand is in the glove. This appears to be more problematic in the wet hand condition, led by the adhesion of the glove to the skin surface. As the finger slides up and into the finger region of the glove, more friction is likely as there is larger contact area with the hand, than at the opened palm. Manufacturers may dip their gloves in silica to aid reinforcement of their tensile properties, prior to the chlorination step, which changes the properties between gloves of the same bulk material. Also, in the case of NRL, this further prevents latex allergies arising. Manufacturers may also use different chlorination strengths and exposure times. These can all impact the final physical properties of the gloves (14, 38, 198).

The time taken to don the gloves has some correlation to the results obtained from the friction study. There is little difference between the chlorinated and polymer coated friction in the dry state with the NBR gloves. However, in both the NRL and NBR gloves, a higher friction coefficient is induced when moisture is applied. The way the moisture reacts to the material strongly influences the friction. NBR, by nature is polar, whereas NRL is non-polar. Thus, when moisture is introduced, it would be expected to have slightly differing frictional behaviours because of the material interaction. The goniometer results show clear differences in the way the water is interacting with the NBR and NRL surfaces. In the NBR gloves, a low contact angle is observed. This means that there is a high surface energy, which pulls the moisture towards the surface, inducing more wetting (hydrophilic). This moisture addition creates local welding and more interaction with the glove surface will be present via electrostatic interaction (121). The NBR pulling the liquid to the surface causes more contact area with the finger, which increases friction, as shown in Figure 4.21a. Thus, the increased time taken to don the PC NBR glove could be due to the hydrophilic nature of the coating itself, which is used to aid donning, rather than hinder it. On the other hand, the NRL glove exhibits a high contact angle, showing a low surface energy which leads to a low surface wetting (hydrophobic). This means the water would have a stronger affinity for the skin, causing a separation of the skin-glove surfaces and adding lubrication to the system, as shown in Figure 4.21b. This allows for the skin to glide smoothly, allowing a quicker donning of the NRL glove, when compared to the NBR. In the NRL, the polymer coating exhibits the lowest friction amongst the participants, which is not highly impinged by the addition of moisture. This difference in friction between the chlorinated and polymer coated NRL gloves is also observed by Roberts and Brackley (137), who obtained friction coefficients of 0.15 for polymer coated and 0.5 with chlorinated gloves at 0.32 N. In this study, friction coefficients for the gloves are found to be much higher. The average CoF for chlorinated gloves in all participants at 0.32 N (following the trendlines) is in a range between 1.23 and 4.03. The CoFs for the polymer coated gloves were also found to be much higher than in the previous study (between 1.12 and 1.23). However, it is unknown what polymer coating has been used in either of the studies.

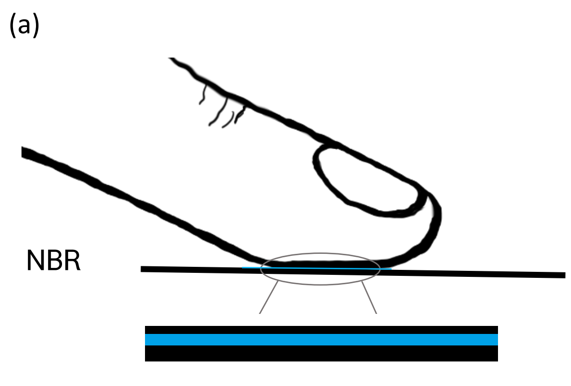


Figure 4.21. Interaction between different glove surfaces when water is introduced. NBR brings the finger to the surface due to the polar nature, whereas NRL repels water, causing it to lubricate.

The explanation behind the proposed interactions can be further evidenced by the friction graphs. Figure 4.22 shows a typical graph of the glove friction obtained in these results. In some participants, after a few seconds, friction started to increase in all gloves when moisture was added. This was predominantly observed in the NBR gloves, more so with the polymer coated, as the hydrophilic nature allows spreading of the moisture, ultimately increasing the skin-NBR contact area. In the NRL gloves, this was more apparent at the higher loads, as the moisture is pushed out of the side of the finger, inducing more contact area.

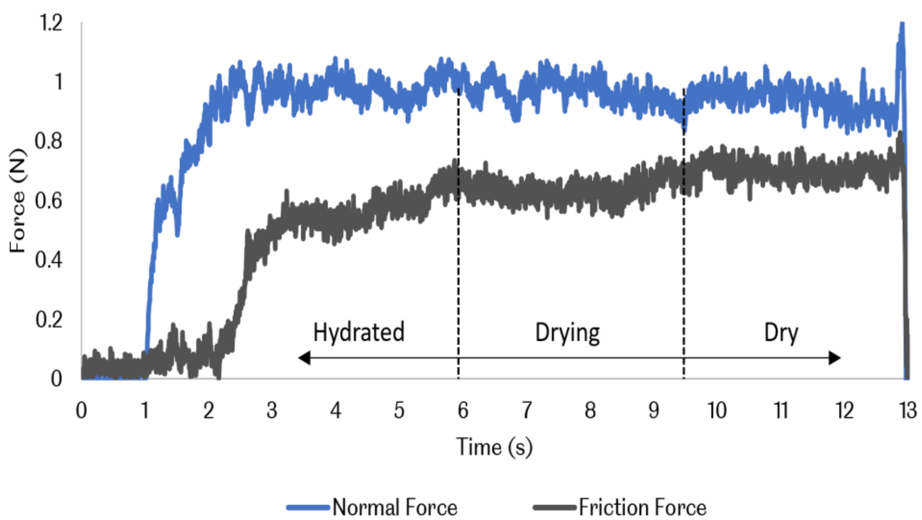


Figure 4.22. Friction of PC NBR gloves showing how the moisture changes in the wet condition increase friction overtime as a sliding interaction with the glove spreads moisture away from the finger surface in contact.

It is also important to note, that the process of coating NBR gloves is not as straight-forward as coating NRL gloves. Close attention needs to be paid to the surface tension of the wet NBR film. Without adequate modification of this surface tension, the polymer coating deposited onto the film can be distributed with an uneven thickness (14, 199). In conjunction with this, high surfactant content from the NBR gloves can leach into the polymer coating bath, causing issues whereby the coating does not bind well to the surface (200). However, these issues are not widely discussed in the literature. This could be one of the reasons for the polymer coated NBR gloves to have higher CoF than the polymer coated NRL.

Morphological changes

Changes in the morphology in the finger throughout the study in both the dry and wet conditions can contribute to slight differences in frictional properties, a variable factor in this study (108, 121, 201). Repeated wetting of the skin fingertip could cause wrinkling of the skin, affecting the contact area and overall frictional properties of the skin. Although this was not visibly noticed, and there was little constant exposure to water/breaks between friction tests, there is still the possibility of micro-wrinkling having an impact on the results (183). As low loads are used in this study, the small changes in the skin topography could have an impact on these results.

Secretion-water interaction

The differences in the donning time and friction in some of the participants may be attributed to skin contaminants. Skin, by nature, contains secretions of moisture, salts, and lipids on the surface, from the underlaying sweat glands (202). This sweat held on the surface can attract or repel the water, causing differences in electrostatic properties, which could cause either a reduction or increase in friction (203, 204). As the contaminants on the fingers interact with the water, two things could occur, which are dependent on the volume of contaminants, and their affinity for the glove material or skin. The sweat-water molecules could pull down towards the polymers, causing a spreading of the moisture throughout the contact area and beyond as the polymer acts as a capillary. This would lead to an increase in contact area as surface asperities are brought closer together, as well as electrostatic interaction with the glove film.

The other mechanism could be a reduction in friction as the moisture stays on the skin surface, causing more separation between the finger and the gloves. This would cause a more complex interaction as the individual contaminants (oils and water) would separate, due to their immiscibility. Although the hands were washed prior to testing there is no guarantee, when conducting studies of this nature, that these contaminants were not present. It is possible that, although small, the immiscibility of these contaminants from sweat contribute to the stick-slip exhibited in some of the gloves. Stick-slip is defined as rapid alternation between the static and dynamic friction. Derler and Rotaru (205) previously defined stick-slip as the measured CoF with a greater than 10% variation, which was observed in some participants (as shown in Figure 4.19). This means that both the donning and friction of the gloves is dependent on how much water the materials will absorb/repel, the interaction between the water and the finger, and the presence of oils/contaminants on the skins surface.

Perception

As discussed by Mylon *et al.* (7), the perception of performance with routine medical glove users is normally indicated by preference. The gloves used amongst the participants in their daily work were chlorinated NBR and NRL gloves. On average, chlorinated natural rubber NRL was perceived to be the easiest to don, but the results indicate that those gloves took longer to don whist the polymer coated NRL was the quickest. Some participants also stated that the polymer coated NRL gloves were harder to put on because they felt thicker than any of the other gloves, but the thickness was similar to the polymer coated NBR.

4.5.2 Doffing

Doffing was not viewed to be an issue in this study. The results showed no differences between the gloves. There was an increase in the time taken to doff the gloves when moisture was present, however, this increase was minor and had no significant differences. In the PC gloves, there is a tendency for NBR to take longer to don when compared to NRL. This is presumably because of the hydrophilic nature of the NBR being drawn towards the skin. This would mean there is likely a stronger interaction brought about by electrostatic charges between the skin and glove, causing more of a peeling action to remove the gloves. In the NRL, however, the moisture will be separating the glove from the skin, leading to a smoother transition when removing the glove, as described in the donning actions. Very few participants thought that the different glove materials and coatings affected their ability to remove the gloves, indicating that doffing is not an issue with these glove users. However, the gloves were removed soon after donning, it may be that when more sweat is generated in the glove, issues with glove sticking to the hands could cause more adhesion, possibly making it harder to doff the gloves. Most participants indicated that all the gloves were easy to doff, but a few commented that the polymer coated gloves ‘felt thicker’ and perceived that to be a slight hindrance upon removal.

4.5.3 Glove properties

The gloves have been tested under EN standards; however, it is not known how old the gloves are before these tests were conducted. Donning assessments were carried out around 1 year prior to testing the physical parameters, and it was unknown when the gloves were manufactured prior to the donning testing. Gloves degrade over time, and the longevity of their physical properties is dependent on the correct storage, light exposure (206) and relative temperature/humidity (207). It is very likely that this is not a true representation of the properties of the gloves when formed. For this reason, the physical properties were not checked for correlation between either the donning or physical properties with these gloves. This is because it is thought that this is not replicable of what the properties will have been when the tests were conducted.

The differences in thickness along the glove length can be explained by inverted nature of the dipping process of the glove manufacture procedure. When gloves are made on the dipping line, formers are dipped into the compounded glove material finger first, left for the dwell time (usually 5-10 seconds), and then then pulled back out of the compounded material. Therefore, the finger areas have a longer dwelling time in the material, and have more coagulated rubber onto the surface of finger areas, which produces a thicker film when compared to the palm (14, 38).

Issues were noticed when donning the gloves, mostly around the rolling of the glove on the back of the hand, as shown in Figure 4.23. This adds time to the 'after manipulation' stage of donning as participants take the time to unroll the glove and bring the cuff up the wrist to complete the donning process. This rolling was more commonly seen in the NRL gloves. As the glove begins to roll up the back of the hand, the chlorinated NRL glove will continue to roll with it due to it being less stiff and conforming more to the hand. The NBR material, however, is stiffer compared to that of the NRL and appeared to roll on the back of the hand less frequently, and not as severely. The gloves were of a similar thickness except for the chlorinated NBR which was almost half the thickness of the other gloves on average. As there are no statistically significant differences between the dry handed gloving conditions, it is indicated that the thickness of the glove is not a factor in this study. However, the lack of difference could be due to the differences in skin-glove coating interactions. Further work needs to be carried out to assess if, and how, the thickness of gloves affects the donning process.

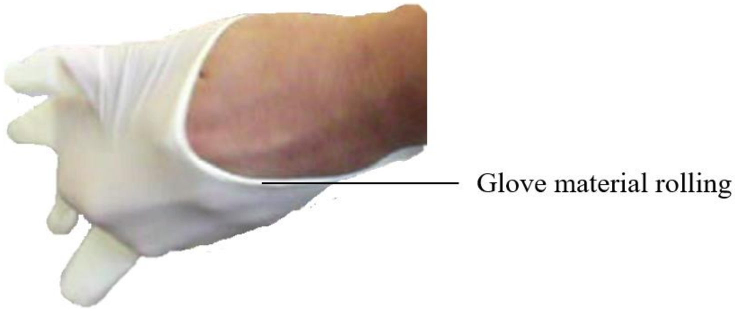


Figure 4.23. Rolling of glove on the back of the hand when donning.

4.5.4 Fit

When compared to the recommended glove sizes by the HSE, the participants did not appear to wear the correct recommended sizes. Seven out of the 14 participants wore a size larger than recommended and only one participant wore the correct recommended glove size. The literature shows that these gloves need to be a good fit to ensure maximum comfort, dexterity, and tactile sensitivity (99). As there was a small amount of excess material around the fingers for three of the participants, it was viewed that the gloves were larger than needed when fitted. These three participants wore medium gloves and said that when smaller gloves are used, they are difficult to put on and too tight once on. It would be expected that if the hands are smaller than the recommended glove size, they would be easier to don. However, this is not the case as the time taken to don the gloves were similar across all participants. It is clearly indicated from this study that the 'best-size' to fit a participants' hand has little relation to the recommended 'best-fit' gloves size.

4.6 Conclusions

A summary of the findings from this chapter are shown in Table 4.8. This shows the results of the three tested parameters in this chapter, when comparing the wet hand to the dry hand condition. In all of the tests with NBR, the wet hand complicates the process and increases the time taken to don the gloves and increases friction.

Table 4.8. Findings of the chapter comparing the outcome of performance of the wet hand to the dry hand condition.

	Glove donned in the wet hand condition			
	NBR		NRL	
Measured parameter	**Chlorinated**	**Polymer Coated**	**Chlorinated**	**Polymer Coated**
Donning Time	Increases	Increases	Increases	Increases/Similar to dry
Doffing Time	No difference	No difference	No difference	No difference
Friction	Increases	Increases	Increases	Decreases/ Similar to dry

The conclusions of this chapter are as follows:

- When the gloves were donned in dry conditions, the performance times were similar across the gloves. However, polymer coated NRL generally exhibited lower friction, had less incidences of sticking, and took less time to don when the glove was wet. Little difference was observed in the friction between the dry and wet conditions with the polymer coating in the NRL, however greater differences were noted in the NBR, with the polymer coated having greater friction, and the gloves took longer to don on average. The two chlorinated gloves used had little difference in donning time, but lower friction was observed in the NRL gloves.
- Doffing is not affected by glove material, coating, or hand condition. It could be that prolonged periods of wearing could induce more sweat, making the gloves harder to remove. This would be reflected by the 'wet' condition in this study, which shows no difference from the dry condition.
- The entire donning process needs more thought in studies, other than just the frictional properties. The nature of the material, size, fit and stiffness can all contribute to the glove donning process, and cause problems, such as the glove rolling up the hands, or adhesion of the gloves to the hands.
- There are issues with glove size amongst some glove users. HSE recommendations match only one participant in both palm and finger sizes in this study. Some participants wore sizes that were a little too big for their hands.
- Chlorinating gloves is extremely common, but the finishing processes are not widely revealed to the purchaser/user. Manufacturers may dip their gloves in silica to aid the reinforcement of their tensile properties, and some manufacturers may use different chlorination strengths. Thus, the two chlorinated gloves in this study may not have had the same treatment.

Chapter Five: The effects of NBR glove properties on donning

5.1 Introduction

In Chapter 4, it was shown that the choice of polymer coating in the NBR material was more detrimental to the donning process than the chlorinated gloves. The study conducted, however did not study the effects of the effects of thickness but indicated that there was little difference in results regarding thickness in the dry condition (172). Nor did the experiments have the capability of making the test fair, by comparing gloves that only differed by their raw materials and treatments/coatings. When purchasing gloves, it is impossible, without the manufacturer's information, to determine the exact components used and the treatment methods. There are a range of ways manufacturers can finish gloves. This includes dipping in silica to protect the physical properties, ranging chlorination strengths and the length of exposure to the chlorination (14, 38, 198). A higher chlorination leads to a smoother surface, reducing tack and ultimately reducing the friction (16, 173). However, there is little to link this chlorination process to an easier donning process, especially in the way of human skin friction in conjunction with the donning mechanisms (173). In order to study the effects of chlorination with skin, gloves need to be made with the same materials.

5.2 Aim and scope

The aim of this study covered in this chapter was to investigate the effects of thickness, chlorination strength, and moisture on the donning process. To study the effects of thickness and chlorination, gloves needed to be sourced which had the same manufacturing profiles and only differed in surface treatment and thickness. In order to obtain these, gloves had to be manufactured specifically for this test. Due to the leaning of the sales market towards the NBR gloves, only this material was studied for the effects of different chlorination strengths and thickness (38). As with Chapter 4, the donning of gloves was assessed in both dry and moist conditions.

5.3 Materials and methodology

5.3.1 Glove manufacture

NBR gloves were produced in-house at the Technical Centre of Synthomer Sdn Bhd, Kluang, Malaysia. The NBR films were formed using Synthomer 6348HS grade rubber, via two manufacture methods which mimic the process used for standard glove manufacture, but on a smaller scale. Synthomer

6348HS is a colloidal suspension of carboxylated acrylonitrile butadiene, containing emulsifiers and antioxidant stabilisers. The manufacture methods used in this study differed only by the dwell time of the former dipped into the coagulant and the compounded NBR material, in order to create gloves of two different thicknesses.

Glove formation

The NBR was compounded using the constituents shown in Table 5.1. Medium size porcelain glove formers were placed into a mixture of calcium nitrate and calcium carbonate coagulant for three seconds. The formers were then heat dried in a 65°C oven before being dipped into the compounded NBR for a further three seconds (Figure 5.1). Following this, the formers were placed into an oven to gel set at 100°C for one minute, before being dipped again for a further three seconds. This method created the thinner of the two films. The thicker film was produced using the same approach, but with double the dwell time (six seconds for compounding and dipping). After the gelling process, the gelled films were manually beaded. The beading was achieved by rolling the end of the glove down a few mm, which creates the cuff of the gloves. The films were then leached for one minute in water at 100°C and then left to cure at 100-120°C in an oven to create the finished glove. Due to the availability of equipment and small-scale production, films were only manufactured on medium sized formers.

Table 5.1. Components used to make compounded solution of the NBR material for the glove film formation

Component	Parts per hundred rubber (phr)
6348HS NBR	100
Potassium Hydroxide	1.2
Zinc oxide	1
Sulphur	0.8
Zinc diethyldithiocarbamate	0.7
Titanium dioxide	1.5

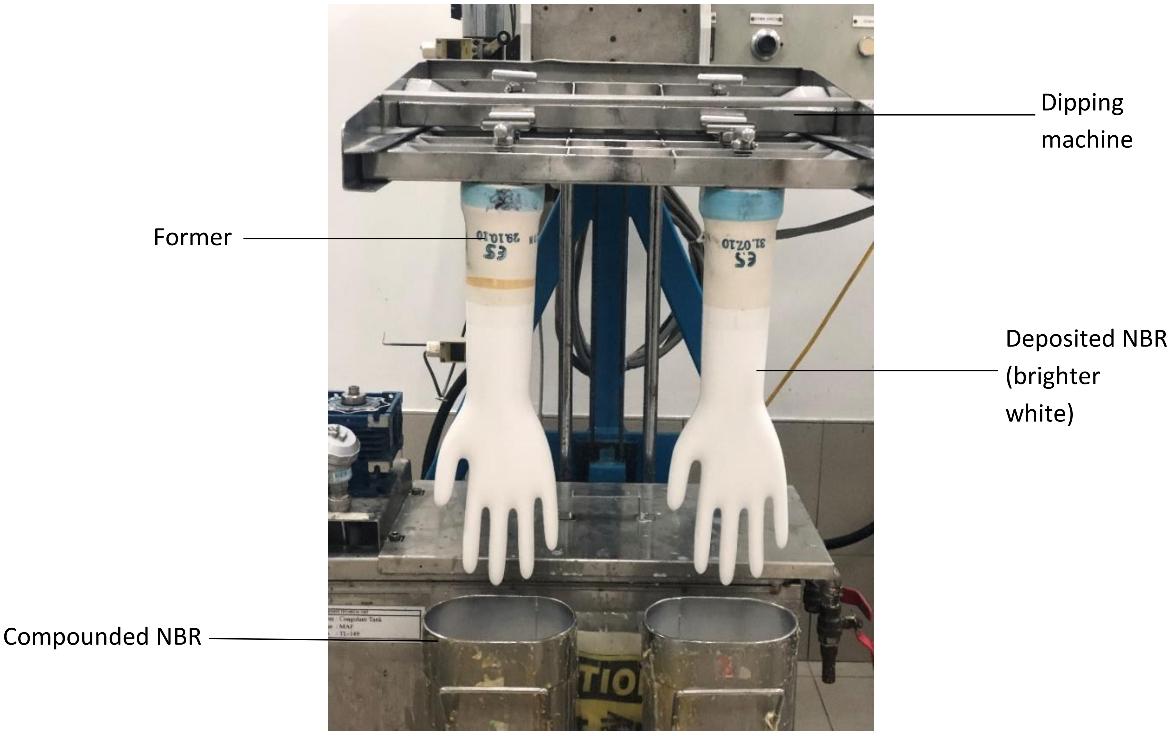


Figure 5.1. NBR material coagulated on the former surface (covered by coagulant salts) to form the wet NBR film.

Chlorination

For this research, the acidification process was used, as discussed in Chapter 2 (53). Sodium hypochlorite and hydrochloric acid (HCl) were mixed to create the concentrations in large plastic containers, in which the formers could be immersed. Chlorine solutions were created at concentrations of 500, 1000, and 2000 ppm (parts per million of chlorine). These concentrations were chosen based on the typical industrial practices reported in Ong (16). A quarter of the gloves from each thickness variant were skipped for the chlorination process to serve as control for testing. Formers containing the attached glove film were placed into the chlorine solutions for 10 minutes. Following this, formers were then immersed in a neutraliser solution (sodium thiosulphate) for 6 minutes before being leached, at 60°C with hot water. This removes any chlorine residue on the film surface. The films were then dried in an oven for 5 minutes at 100-120°C, before being removed from the former. One of the aims of this study was to assess to what extent chlorination made the whole donning process easier, including a control which had no treatment. However, the control gloves were found to be hard to release from the formers and became overstretched/torn. Thus, the control glove was covered in a light dusting of calcium carbonate, which helped release the glove from the contours of the former. Attempts were made to keep the powder distribution minimal, however, the fine powder is likely to still be present on the inner surface.

Glove characterisation

The gloves were characterised as in Chapter 4, using the same thickness and size, tensiometer and goniometer measurements (see Section 4.4). As it was found that strain did not affect the contact angle, these were measured with the gloves in the unstrained condition. Also, in this section, two extra tests were conducted on the gloves: surface characterisation by surface roughness and Fourier transform infrared spectroscopy (FTIR).

Surface Roughness

Surface roughness of the donning side of the gloves was measured using Alicona optical 3D measurement. In Chapter 4, the ability to measure the surface roughness was not possible due to the nature of the finish on the materials. As the finish on these gloves rendered a 'duller' surface finish, roughness was able to be obtained. Two samples of approximately 4 × 4 cm samples were cut from the finger area of two separate gloves. For surface analyses, 1.5 × 1.5 cm sections were scanned onto the instrument to obtain an average surface roughness (S_a) of the gloves, with a 5x objective lens with magnification between -1.46 – 15.85x, a lateral resolution of 2.89 μm, and a vertical resolution of 900 nm.

FTIR

A Thermo Scientific (T1-139) Fourier transform infrared spectrometer (FTIR) was used to assess the chemical differences on the inner (donning) surface of the different manufactured gloves. This was to establish if there were any chemical differences between the gloves receiving different chlorination strengths. Each sample was scanned 16 times in the 400-4000cm^{-1} region with a resolution of 4cm^{-1}.

5.3.2 Experimental methodology

The donning methodology was completed following the same set-up and procedure as in Chapter 4 (see Section 4.4). This study was conducted in the same conditions; dry and wet. There are, however, a few differences between this study and the one previously conducted in Chapter 4, which are as follows:

- The participants donning the gloves were not regular day-to-day glove users but use gloves 1-2 times a week on average. Thus, perceptions of donning/doffing were not ascertained.

- Moisture was measured on the fingers, palm and back of the hand using a moisture sensor before trying on each glove type in dry and wet conditions.
- A drawback of the in-house manufacturing was the time taken to produce gloves on a small batch scale, resulting in a lower volume of gloves being manufactured. Thus, the number of participants was less than half of that of the previous study (n=6).
- Friction was measured in the same way as previously (see Section 4.4.3). However only three loads were tested to allow time to repeat tests in an efficient manner. The selected loads were the low (0.1N), medium (0.5N) and high (1N) loads used in the previous study.
- An extra friction study was used to determine the effects of the sample properties on the donning behaviour. This was conducted by only affixing the glove around the edges of the force plate. This left the centre free to move with the fingers, allowing assessment of the behaviour of the different sample thicknesses.
- The doffing of these gloves was not assessed due to it not being highlighted as an issue in Chapter 3, nor were there any differences between gloves in the previous study.

Participants

For the donning part of this study, four males and two females participated in this experiment (n=6). Ages ranged between 22-28, and they did not have any known skin issues or any allergies that could be triggered by using gloves. Participants used gloves on average 1-2 times per week and had a preference of wearing 'medium' sized gloves. Hands were measured in the same manner as the previous methodology in Chapter 4 (see Section 4.4). Prior to being recruited, participants were asked to don a pair of the gloves to allow an assessment of fit. These gloves were picked at random, and which glove was tried on was not noted. There did not appear to be any visual issues with fit once the gloves were donned. Nor were there any comments around the fit of the gloves and participants stated the gloves fit as they would expect.

Moisture

To assess the moisture present on the hands during the donning process, MoistSense readings were taken in three regions. One reading at each of the fingers/thumb tip. Two readings at the top of the palm, one in the centre and two at the base of the palm. The final set of readings were taken at the back of the hand. Two were taken below the knuckle, one in the centre and two at the base of the back of the hand. A diagram of the measurement locations is shown in Figure 5.2. These locations were picked due to their likelihood of contact with the skin as noticed in the previous study. The donning procedure was conducted as soon as the moisture measurements were taken.

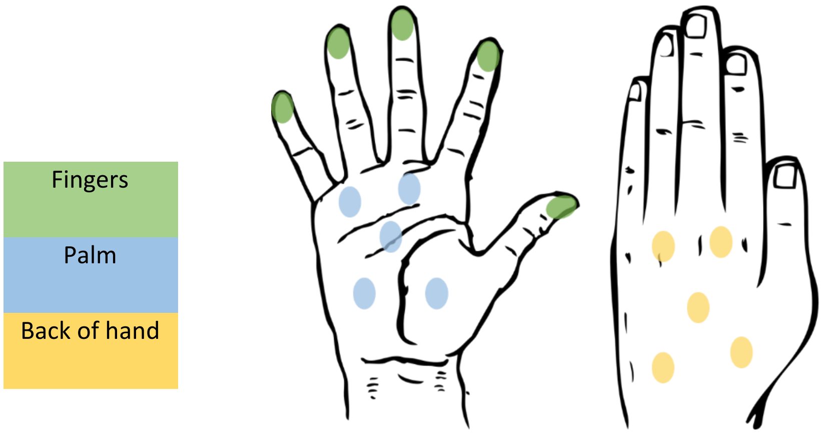


Figure 5.2. Diagram of hands where measurements were taken.

5.3.3 Analysis

The analysis follows as described in Chapter 4. In conjunction with this study, friction measurements were carried out on three of the participants who took part in the donning study (2 males and 1 female, aged 26-28). As these participants took part in both tests, correlations between measured friction and donning performance could be examined. These correlations were assessed using Pearson correlation regression analysis (208). .

5.4 Results

5.4.1 Physical properties

The results obtained from the mechanical testing of the gloves are shown in Table 5.2. This provides the sample IDs of the gloves used in the following results and discussions, and the measured parameters, as well as the calculated stiffness (using the equation in Chapter 4, see Equation 4.1).

Table 5.2. Results of physical testing of the gloves under EN standards and calculated stiffness. Where T= thickness, Fb= force at break, Ts= tensile strength, Eb=elongation at break and K= stiffness.

Sample ID	Chlorination Strength (ppm)	T (mm)	Fb (N)	Ts (MPa)	Eb (%)	K (N/mm)
A	500	0.054 (±0.003)	6.50 (±0.49)	39.90 (±2.88)	506.58 (±25.69)	0.022 (±0.003)
B	1000	0.054 (±0.004)	6.93 (±0.55)	42.79 (±3.37)	511.00 (±16.73)	0.030 (±0.006)
C	2000	0.055 (±0.004)	6.71 (±0.80)	40.96 (±3.40)	489.00 (±23.63)	0.030 (±0.009)
D	0	0.059 (±0.003)	6.93 (±0.90)	38.97 (±4.93)	436.00 (±39.06)	0.026 (±0.003)
E	500	0.098 (±0.003)	16.50 (±1.12)	56.00 (±3.64)	528.50 (±10.88)	0.059 (±0.003)
F	1000	0.100 (±0.005)	16.30 (±1.14)	54.55 (±3.45	502.83 (±16.35)	0.059 (±0.005)
G	2000	0.104 (±0.004)	17.64 (±2.23)	56.78 (±7.68)	526.75 (14.67)	0.059 (±0.005)
H	0	0.103 (±0.006)	17.23 (±1.45)	55.98 (±4.65)	523.00 (13.82)	0.055 (±0.004)

± denotes standard deviation

The stress-strain curves obtained from the sample strength testing are shown in Figure 5.3. The thicker gloves chlorinated at 1000 ppm (F) shows the highest stress at 500% strain, with the thin 500 ppm (A) sample showing the lowest stress at 500% strain. Only one glove sample ruptured before 500% strain, which was the thinner control (D). The average elongation at break of sample C was also below the 500% strain (489.00 (±23.63) %), however some of the samples did break after the 500% strain, and the pattern of deviation puts the average before the 500% strain measured. This suggests the chlorination process has provided the gloves with a greater elastic modulus; however, this is not observed in the thicker gloves as all the moduli are in the same region. However, sample F does have a slightly higher modulus than the other thicker glove chlorination strengths and the control.

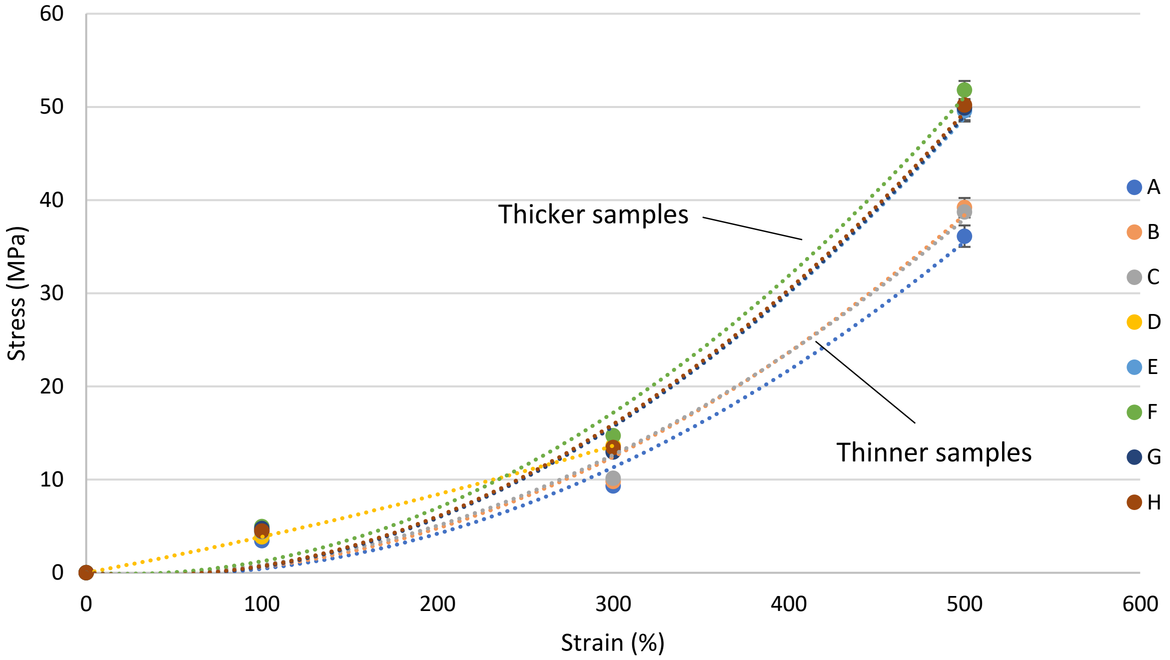


Figure 5.3. Stress-strain curves of each in-house formed glove. Error bars indicate standard error.

Statistical analysis

Thickness

ANOVA tests carried out show no significant differences in thickness across the thicker gloves at different chlorination strengths ($F(3, 44)=2.951$, *p=.059*). However, statistically significant differences in thickness are shown in the thinner gloves ($F(3, 44)=5.877$, *p=.002*). Tukey's (HSD) tests (Table 5.3) reveal that the differences are present between gloves A, B and C when compared to the control (*p<.05*).

Table 5.3. Tukey's (HSD) test carried out on thinner gloves.

		p-Value		
	Glove sample	**B**	**C**	**D**
p-value	**A**	*Q=0.162 p=.900*	*Q=0.243 p=.900*	*Q=4.864 p=.007**
	B		*Q=0.4053 p=.899*	*Q=5.026 p=.005**
	C			*Q=4.621 p=.011**

**Denotes statistical significance (p<.05).*

Tensile strength

No significant differences in tensile strength are present throughout the two sets of glove thicknesses following ANOVA tests (thin $F(3,44)=2.319, p=.089$; thick $F(3,44)=0.392, p=.760$). Thicker glove samples exhibit greater tensile strength than the thinner samples, which was expected due to the thickness being double that of the thinner samples.

Force at break

Chlorination does not appear to have affected the break force of the either the thicker or thinner glove samples, as no significant difference is present between any of the strengths following ANOVA tests thin ($F(3,44)=1.061, p=.375$; thick $F(3, 44)=1.960, p=.134$). As expected, a higher force is required to break the thicker gloves, when compared to the thinner. Overall, the results show that in the thicker gloves, glove G (2000ppm) gives the highest force break (17.64 N) amongst the chlorinated gloves. However, in the thinner samples, glove B (1000ppm) shows to have the highest break force at 6.93 N (±0.55).

Elongation at break

ANOVA testing shows that the elongation at break is significantly different across both the thinner ($F(3,44)=18.817, p=<.001$) and thicker $(F(3,44)=14.986, p=<.001$) gloves. In the thinner samples, the chlorination process has shown to significantly increase the elongation at break as all chlorination strengths (A, B, & C) are significantly higher than the control (D) via the post-hoc Tukey's (HSD) testing (Table 5.4). The thicker gloves, however, show differences in the chlorination strengths following post-hoc testing. Differences are shown to be statistically significant between sample E and F ($Q=6.320, p=.004$) as well as E and G ($Q=8.153, p=.001$). Differences are also present between the control (H) and the other two chlorinated gloves (F and G).

Table 5.4. Tukey's (HSD) test carried out elongation at break results after ANOVA results for both thick and thin gloves show significant differences (thin F(3,44)=1.061, *p*=.375; thick F(3,44)=1.960, *p*=.134).

		p-value				***p-value***		
		Thin gloves				***Thick Gloves***		
	Glove	**B**	**C**	**D**	**Glove**	**F**	**G**	**H**
p-value	**A**	*Q=0.556 p=.898*	*Q=2.215 p=.410*	*Q=8.892 p=.001**	**E**	*Q=5.127 p=.004**	*Q=8.440 p=.001**	*Q=1.099 p=.085*
	B		*Q=2.772 p=.220*	*Q=9.448 p=.001**	**F**		*Q=3.313 p=.104*	*Q=4.029 p=.031**
	C			*Q=6.677 p=.001**	**G**			*Q=7.341 p=.001**

**Denotes statistical significance (p<.05).*

Stiffness

Stiffness is found to be similar in the thicker gloves which are chlorinated (on average 0.059 N/mm), however more variation is noted in the thinner gloves (Table 5.5). Sample A has a lower stiffness at 0.022 (±0.003) N/mm, whereas B and C have greater stiffness at 0.030 N/mm which leads to significant differences in the ANOVA test (*F(3,44)=4.774, p=.006*). Significant differences are noted between gloves A with B (*Q=4.585, p=.012*) and C (*Q=4.683, p=.010*). This is also noted in the thicker glove samples (*F(3,44)=7.887, p=<.001*), whereby glove E shows significant differences in stiffness to glove F (*Q=5.731, p=.001*) and glove G (*Q=5.798, p=.001*). Sample A also shows a lower stiffness than the non-chlorinated control 0.026 (±0.003) N/mm, although this is not significantly different (*(Q=1.578, p=.663*).

Table 5.5. Tukey's (HSD) test carried out on the stiffness of the glove samples after ANOVA results for both thin *(F(3, 44)=4.774, p=.006*) and thick (*F(3, 44)=7.887, p=<.001*) show significant differences.

		p-value				***p-value***		
		Thin gloves				***Thick Gloves***		
	Glove	**B**	**C**	**D**	**Glove**	**F**	**G**	**H**
p-value	**A**	*Q=4.585 p=.012**	*Q=4.683 p=.010**	*Q=3.106 p=.141*	**E**	*Q=5.731 p=.001**	*Q=5.798 p=.001**	*Q=2.427 p=.328*
	B		*Q=0.099 p=.900*	*Q=1.479 p=.702*	**F**		*Q=0.067 p=.900*	*Q=3.304 p=.105*
	C			*Q=1.578 p=.663*	**G**			*Q=3.371 p=.095*

**Denotes statistical significance (p<.05).*

5.4.2 FTIR

Results of the FTIR spectra are shown in Figure 5.4. Some slight differences exist between the chlorinated samples. These differences pertain to absorbance only, indicating that there are some small changes to the frequency of functional groups present on the samples, but ultimately the samples have similar spectra. The thicker gloves tend to have less absorbance of the functional groups, but all samples have the same spectral patterns. However, the control samples do have some noticeable differences to the chlorinated samples. Samples D and H show a major absorbance at 1450cm^{-1}, which shows a much stronger presence of methylene groups (-CH_2-). These are present in the chlorinated samples, but with a much weaker absorbance. At 2512cm^{-1} there are some peak absorbances which correspond to S-H (thiol) stretching, in the samples D and H. This peak is not present in the chlorinated samples. Other notable peaks are present in the controls that are not present in the chlorinated samples. These peaks arise at 1576cm^{-1}, 871cm^{-1} and 712cm^{-1} and correspond to ketenes (C=C=O), H-C=C bending, and C-H bending, respectively. These groups are likely to be changed when the chlorine process is conducted. Peaks present in the 2356-2330cm^{-1} region with samples B, C, G and F correspond to carbon dioxide (209–211). These peaks arise due to a change in concentration in the air around the FTIR instrument and are not considered to be part of the results.

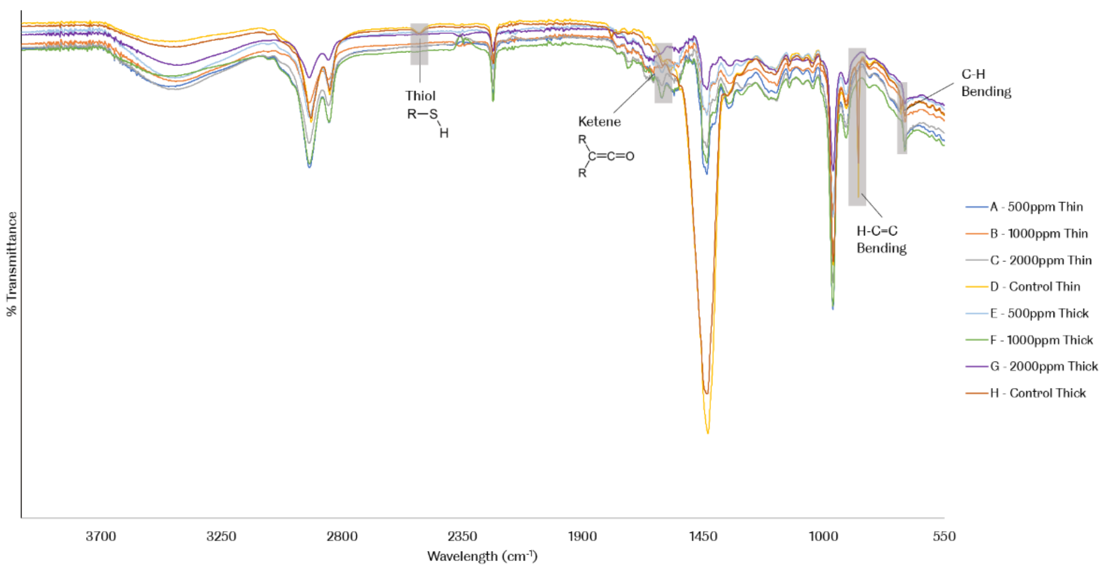
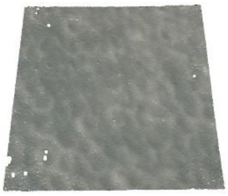
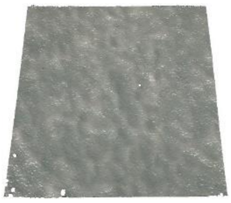
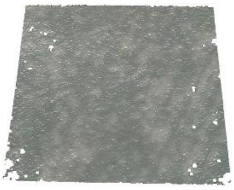
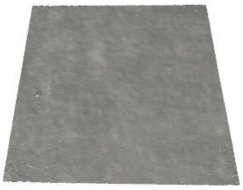
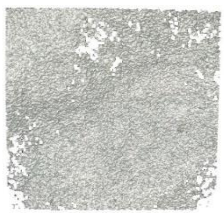


Figure 5.4. FTIR spectra of gloves A-H with major functional group differences highlighted and labelled with corresponding functional groups.

5.4.3 Surface roughness

The results show that the surface area roughness (Sa) decreases as the chlorination strength increases, as shown in Table 5.6. The control samples are found to possess the highest surface roughness (0.44-0.49µm) whilst the highest strength chlorination (2000ppm) is found to be the smoothest (0.18µm). Little differences exist between the thinner and thicker gloves, indicating that the thickness does not affect the surface roughness of the gloves in this study. As both sets of gloves were produced using the same formers, it was expected that roughness would be similar.

Table 5.6. Results from surface roughness measurements of developed gloves.

Chlorination Concentration (ppm)	Thin		Thick	
	Image	Surface Roughness (µm)	Image	Surface Roughness (µm)
500		0.27 (±0.04)		0.22 (±0.06)
1000		0.21 (±0.03)		0.18 (±0.05)
2000		0.18 (±0.02)		0.18 (±0.01)
0 (control)		0.44 (±0.05)		0.49 (±0.05)

± indicates standard deviation between S_a of two separate measurements

5.4.4 Contact angle

The results of the contact angles are similar for all the gloves, which have an average contact angle between 40.0 and 43.4° (Figure 5.5). Similar to the NBR gloves in Chapter 4, there are large overlaps in the standard deviations, which show some variability in the readings. ANOVA shows there are no statistically significant differences for either the thin ($F(3,16)=0.113$, $p=.986$) or thick ($F(3,16)=0.425$, $p=.738$) glove samples, showing the chlorination strength has no effect on the contact angle of the water.

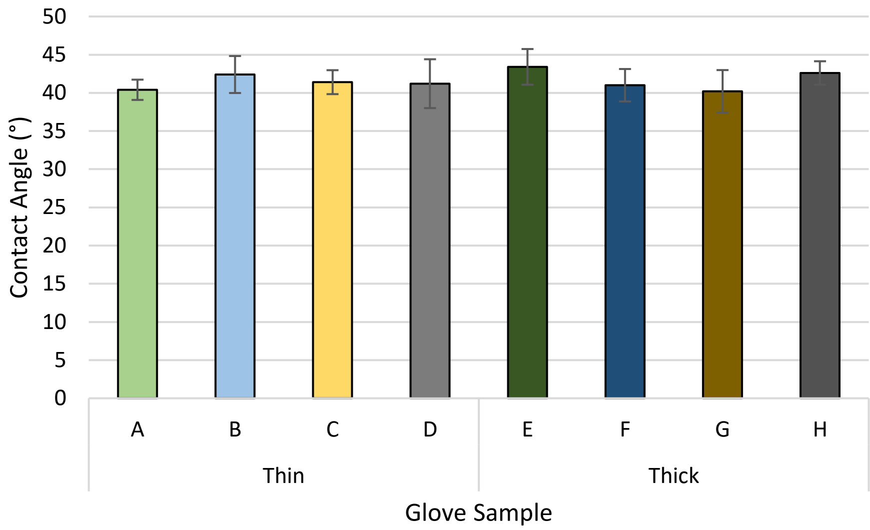


Figure 5.5. Average contact angles of gloves with DI water. Error bars indicate standard error.

5.4.5 Donning

Skin moisture

An average of the moisture results for all participants is shown in Figure 5.6. In the dry conditions, the average moisture between the participants is shown to be 59.23 (±8.85) A.U. for the fingers, 60.55 (±6.70) A.U. for the palm area, and 56.07 (±5.24) A.U. for the back of the hand. After the hands were wettened from washing, the average moisture between the participants is shown to be higher at 93.95 (±2.57) A.U. for the fingers, 94.19 (±2.39) A.U. for the palm area, and 85.15 (±4.49) A.U. for the back of the hand. Wilcoxon signed rank tests were performed between the dry and wet conditions due to non-normal distribution of the data, as determined by the Shaprio-Wilk test. Differences in moisture presence are found to be statistically significant between the two conditions for all the regions tested ($p<.05$).

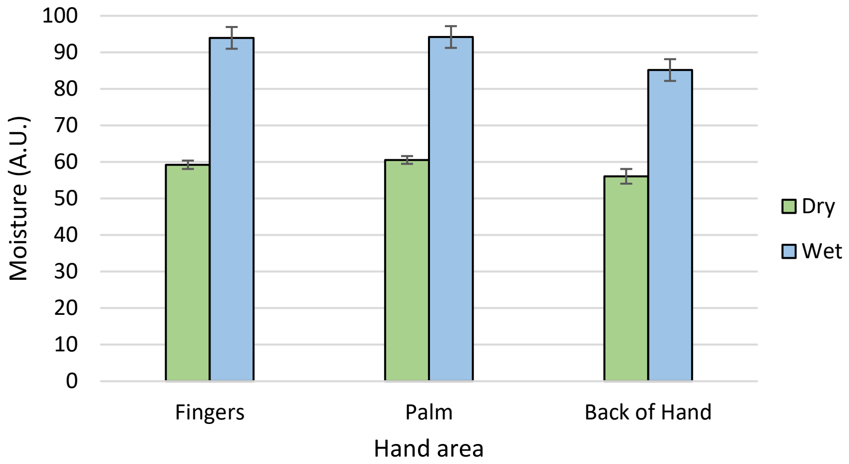


Figure 5.6. Average skin moisture on the hands in dry and wet conditions. Error bars indicate standard error.

Donning time

Table 5.7 shows the average time taken to don one glove. There is an increase in the average time taken to don gloves when the hands had more moisture present, which was also seen in in Chapter 4. Glove C was the quickest to don when dry, taking 10.31 (±2.98) s on average, whilst glove F took the longest, taking 16.12 (±4.56) s on average. When the hands were wet, both controls were the quickest to don, with glove D taking 16.46 (±3.51) s, and glove H taking 18.14 (±3.98) s. Figure 5.7 shows the average time taken for the participants to don one glove in both dry and wet conditions. As with Chapter 4, analysis was only conducted on the three steps of the process where the glove is being used (i.e. the 'pick up' stage has been removed from analysis).

Table 5.7. Total average time taken to don one glove with pick up time removed.

Glove	**Time (S)**	
	Dry	**Wet**
A	13.39 (±2.75)	20.88 (±6.41)
B	11.24 (±2.26)	16.67 (±6.21)
C	10.31 (±2.98)	21.48 (±6.11)
D	12.64 (±1.49)	16.46 (±3.51)
E	16.06 (±6.42)	25.82 (±5.42)
F	16.12 (±4.56)	21.89 (±4.82)
G	11.40 (±3.60)	24.13 (±5.76)
H	12.46 (±3.98)	18.14 (±3.98)

± indicates standard deviation.

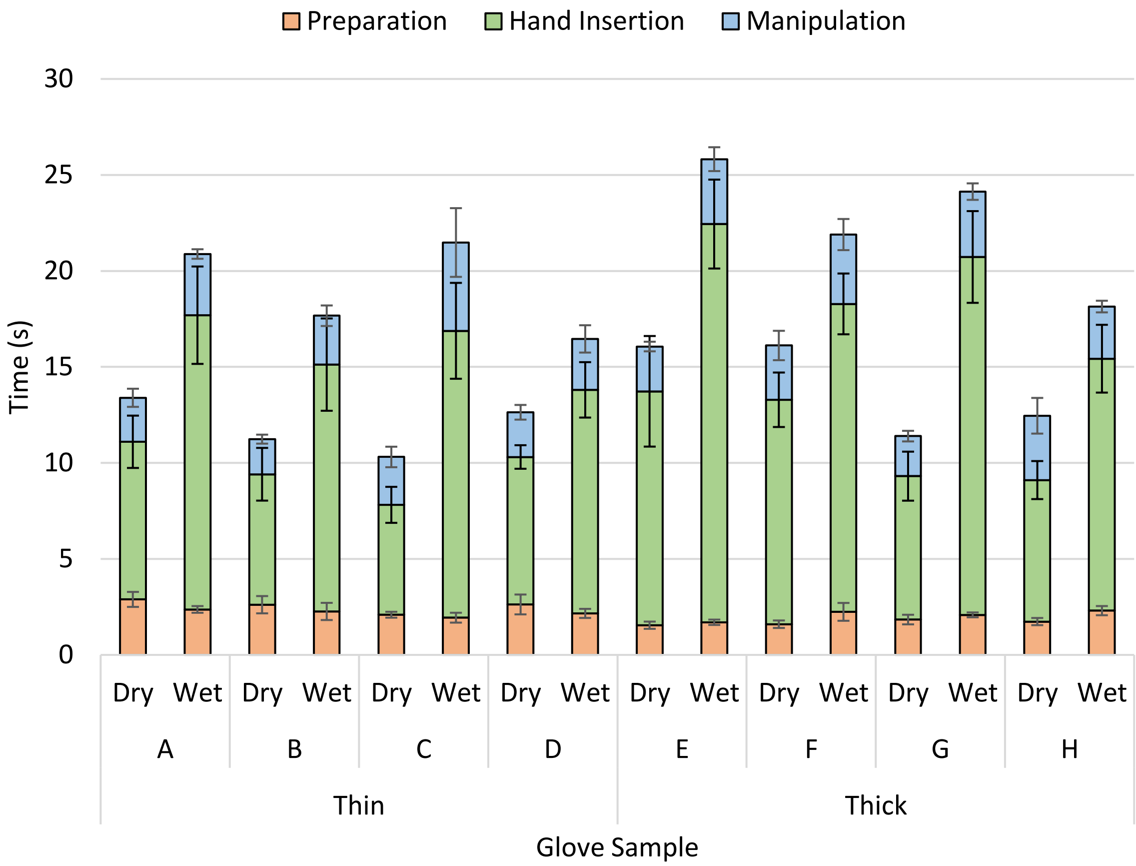


Figure 5.7. Average time taken for each of the three donning steps to be completed for one glove. Error bars denote standard error across the 6 participants.

Thickness

Statistical analysis results are shown in full in the appendix C1. ANOVA tests across the glove thicknesses show no statistically significant differences throughout the thin gloves in either condition (dry $F(3,44)=2.464$, $p=.075$; wet $F(3,44)=1.753$, $p=.170$). However, significant differences are present across the thick gloves in the wet condition (dry $F(3,44)=2.329$, $p=.087$; wet $F(3,44)=2.845$, $p=.048$). Tukey's (HSD) found significance only between samples E and H (Q=3.902, $p=.040$). Statistical analyses were also performed on each step of the donning process. As most of the datasets being compared were non-parametric, Kruskal-Wallis tests for non-parametric data was used to compare thin and thick gloves in both the dry and wet conditions. No statistically significant differences were present between the gloves in the preparation or the manipulation stage of the donning process ($p<.05$, Appendix C1.3-C1.5). However, significant differences were found between the thick gloves in the wet condition during the hand insertion step ($H(3, 44)=8.736$, $p=.019$, Appendix C1.4). This is where most of the differences are observed in the donning process. The hand insertion step was then subjected to a post-hoc Dunn's test for non-parametric data, which shows statistically significant differences between the gloves in E and H (*Z=2.878 p=.002*).

Gloves were also checked for statistical significance at each chlorination strength between the thick and thin gloves. Paired t-tests show no statistically significant differences between thin and thick gloves at each chlorination, except for 1000ppm chlorination when gloves are donned in the dry condition (*t(11)=-2.823, p=.008)*. The smallest difference is observed with the control gloves (D and H), which differ by 0.14 seconds on average between thickness in the dry condition. The largest difference observed is with the 500ppm gloves in the wet condition, which differ by 4.94 s, on average.

Hand condition comparison

Significant differences were found between donning times in the dry and wet conditions with each of the gloves, with the exception of glove sample F *(p>.05)*. Results from the t-tests are shown in Table 5.8. In the preparation and manipulation stages, no statistically significant differences were found for any of the samples *(p>.05)*. In the hand-insertion phase, however, statistically significant differences were found for all glove samples *(p<.05)*.

Table 5.8. Results of paired t-tests between gloves in dry and wet conditions at each stage of the donning process.

Glove Sample	**p-value**			
	Total Time	**Preparation**	**Hand Insertion**	**Manipulation**
A	*T(11)=3.447 p=.001**	*W=18 p=.122*$^{\Delta}$	*T(11)=-3.313 p=.002**	*W=19 p=.158*$^{\Delta}$
B	*T(11)=-2.976 p=.008**	*T(11)=0.672 p=.552*	*T(11)=-3.047 p=.002**	*T(11)=-1.269 p=.145*
C	*T(11)=-4.887 p=.013**	*T(11)=0.467 p=.580*	*T(11)=-4.392 p=.001**	*W=25 p=.159*$^{\Delta}$
D	*W=12 p=.016*$^{\Delta}$	*T(11)=1.121 p=.255*	*W=3 p=.005* $^{\Delta}$	*W=13 p=.502*$^{\Delta}$
E	*T(11)=-3.461 p=.006**	*T(11)=-0.579 p=.588*	*T(11)=-3.116 p=.005**	*T(11)=-1.928 p=.125*
F	*W=14 p=.075* $^{\Delta}$	*W=22 p=.177*$^{\Delta}$	*W=12 p=.047** $^{\Delta}$	*W=32 p=.464*$^{\Delta}$
G	*T(11)=-4.826 p=.001**	*T(11)=-0.755 p=.521*	*T(11)=-5.089 p=.003**	*W=37 p=.107*$^{\Delta}$
H	*T(11)=-2.892 p=.010**	*T(11)=-1.943 p=.828*	*T(11)=-3.332 p=.005**	*W=30 p=.381*$^{\Delta}$

**Denotes statistical significance (p<.05).* $^{\Delta}$ *Denotes Wilcoxon Signed Rank Tests carried out due to either one or both datasets being non-parametric*

5.4.6 Physical parameters to donning time

Measured physical parameters to donning time

It is important to establish if the physical properties, tested by the industries, have correlations to the performance, as this will allow manufacturers to quickly assess the implication different parameters may have on donning. Table 5.9 shows the correlation coefficients (*r*) and statistical analysis obtained from the regression analysis for both the total donning time, and the hand insertion step. The *r* can range from 1 and -1. A value of 0 shows no association between the two variables. Correlation coefficients between 0.3 and 0.5 are viewed as weak positive correlations, whereas above this (0.5-1) are seen as moderate-stronger positive correlations. (212, 213). The hand insertion step has also been included as this is the step where the hand has more interaction with the glove overall. Stronger correlations can be seen in the wet conditions, rather than the dry. The thickness of the gloves shows a moderate correlation to the time taken to don the gloves, which is stronger in the wet condition in the hand insertion step (*r=.557; p=.152*). However, it is shown that the thickness is similar throughout the gloves in each set. While the donning times are not too dissimilar between glove sets, this correlation is stating that the thicker the glove, the longer the glove takes to put on. The elongation at break of the gloves shows moderate correlation to both the total donning time and the hand insertion step, but only in the wet condition. Moderate correlations observed with the force at break have similar correlation coefficients to the thickness parameter, with more correlation being observed in the wet condition. Surface roughness shows moderate correlations to both the total donning time and the hand insertion step in the wet condition only (*r=-.655 and r=-.589*, respectively). This indicates that, as the surface roughness decreases, the donning time increases. However, this is not statistically significant in any of the conditions (*p>.05,* Table 5.9). Tensile strength shows to have moderate correlations to the total donning and hand insertion step. In the wet condition, these are statistically significant (*p<.05,* Table 5.9). This strongly indicates that in the wet conditions, the higher the tensile strength of the glove, the longer it takes to don (Figures 5.8 and 5.9).

Table 5.9. Pearson correlation coefficient results for total donning time and the hand insertion step against the physical parameters, where r is the Pearson correlation coefficient, and *p* is the statistical significance.

	Total donning time to tested parameter									
	Surface Roughness		**Strength**		**Thickness**		**Elongation**		**Force at Break**	
	r	*p*	r	*p*	r	*p*	r	*p*	r	*p*
Dry	-.065	*.878*	.511$^{\lozenge}$	*.196*	.476$^{\Delta}$	*.233*	.171	*.686*	.460$^{\Delta}$	*.247*
Wet	-.655$^{\lozenge}$	*.078*	.726$^{\lozenge}$	*.041**	.510$^{\lozenge}$	*.197*	.599$^{\lozenge}$	*.117*	.534$^{\lozenge}$	*.173*
	'Hand Insertion' step time to parameter									
	Surface Roughness		**Tensile Strength**		**Thickness**		**Elongation**		**Force at Break**	
	r	*p*	r	*p*	r	*p*	r	*p*	r	*p*
Dry	-.206	*.626*	.638$^{\lozenge}$	*.089*	.545$^{\lozenge}$	*.162*	.257	*.539*	.540$^{\lozenge}$	*.167*
Wet	-.589$^{\lozenge}$	*.124*	.770$^{\lozenge}$	*.025**	.557$^{\lozenge}$	*.152*	.627$^{\lozenge}$	*.096*	.583$^{\lozenge}$	*.129*

$^{\Delta}$ *Denotes a weak correlation.* $^{\lozenge}$*Denotes a moderate correlation. *Denotes statistical significance*

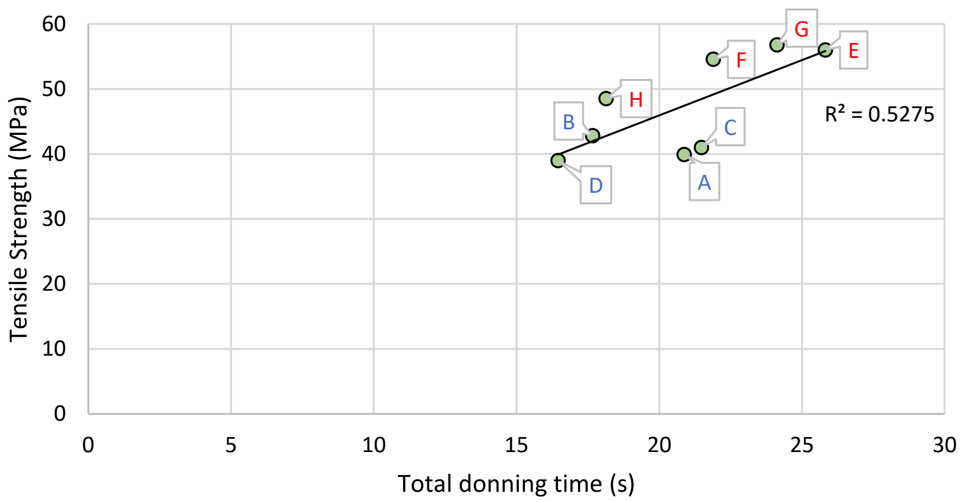


Figure 5.8. Correlation of tensile strength to the total donning time of the gloves in the wet condition. Thin gloves are indicated by blue, and thick gloves by red.

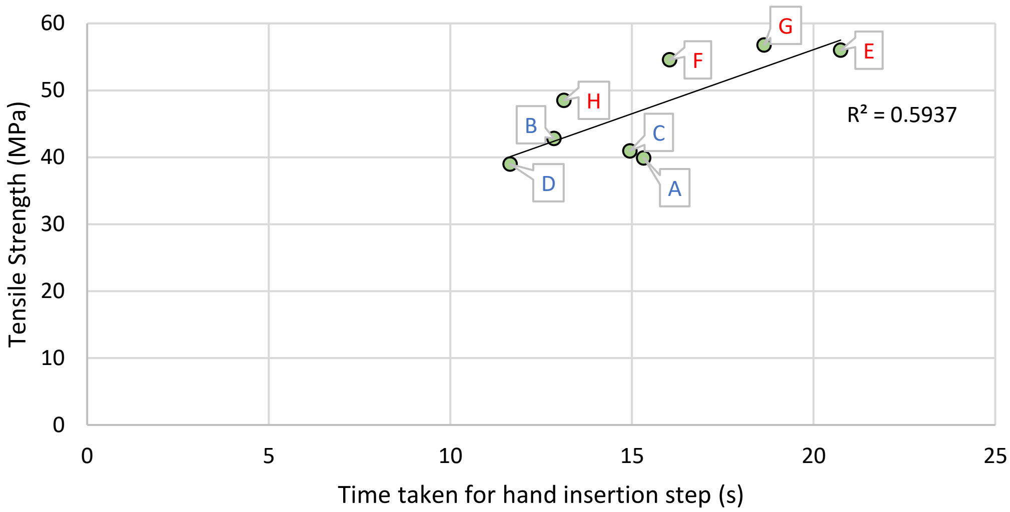


Figure 5.9. Correlation tensile strength to the 'hand insertion' step time of the gloves in the wet condition. Thinner gloves are indicated by blue, and thick gloves by red.

Stiffness and donning time

Stiffness of the material is thought to be an important characteristic when assessing these gloves. Firstly, the stiffness was compared to the physical parameters, to assess if there were any correlations between the measured parameters and the calculated stiffness. Of the parameters, only tensile strength was found to have strong correlations with the calculated stiffness, as shown in Table 5.10. The results shown strong correlations with the measured stiffness at 100, 300 and 500 % strain ($p<.05$). As a greater stiffness is noted in the thicker samples, the results appear as two clusters, as in Figure 5.10.

Table 5.10. Pearson correlation coefficient results comparing the stress at 100% strain and the tensile strength of the samples, where r is the Pearson correlation coefficient, and *p* is the statistical significance.

	Correlation of tensile strength to stress at % strain		
	100	300	500
r	.976¤	.901¤	.991¤
p	<.001*	.002*	<.001*

¤ *Denotes a strong correlation. * Denotes statistical significance*

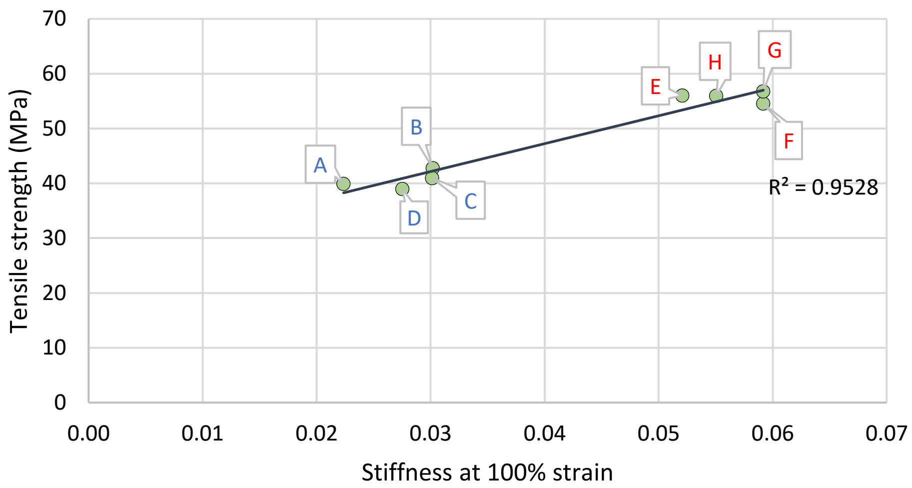


Figure 5.10. Correlation of tensile strength to stress at 100% strain. Thinner gloves are indicated by blue, and thick gloves by red.

As 100% strain is much more likely in the glove donning process, correlations have been drawn against the stiffness at this point, and the time taken to don the gloves. Furthermore, the glove stiffness has also been compared to each of the stages of the donning process, which is shown in Table 5.11. The results show correlations between the steps in the dry hand condition; however, correlations are only found in the total donning time and the hand insertion step with the wet hand condition. Additionally, a statistically significant negative correlation is shown in the preparation stage in the dry condition (*r=-.908; p=.002*). This strongly indicates that the stiffer the glove sample, the quicker participants completed the preparation step (Figure 5.11). However, overall, a moderate correlation is drawn between the total time to don the gloves in the wet condition (*r=.503; p=.204*), compared to the dry condition which shows a weaker moderate correlation (*r=.420; p=.300)*.

Table 5.11. Correlation of donning time to stiffness of each of the samples at 100% strain at the total donning time and each of the three stages of the donning process.

	Stiffness @100% strain							
	Total		**Preparation**		**Hand Insertion**		**Manipulation**	
	r	*p*	r	*p*	r	*p*	r	*p*
Dry	.420[Δ]	*.300*	-.908[¤]	*.002**	.510[◊]	*.197*	.419[Δ]	*.301*
Wet	.503[◊]	*.204*	.221	*.599*	.535[◊]	*.172*	.069	*.871*

[Δ] *Denotes a weak correlation.* [◊] *Denotes a moderate correlation.* [¤] *Denotes a strong correlation. * Denotes statistical significance (p<.05).*

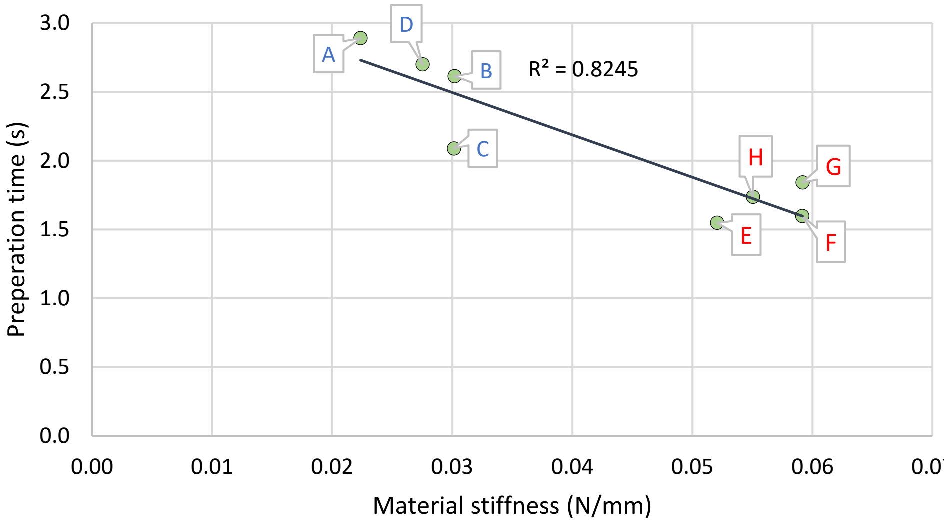
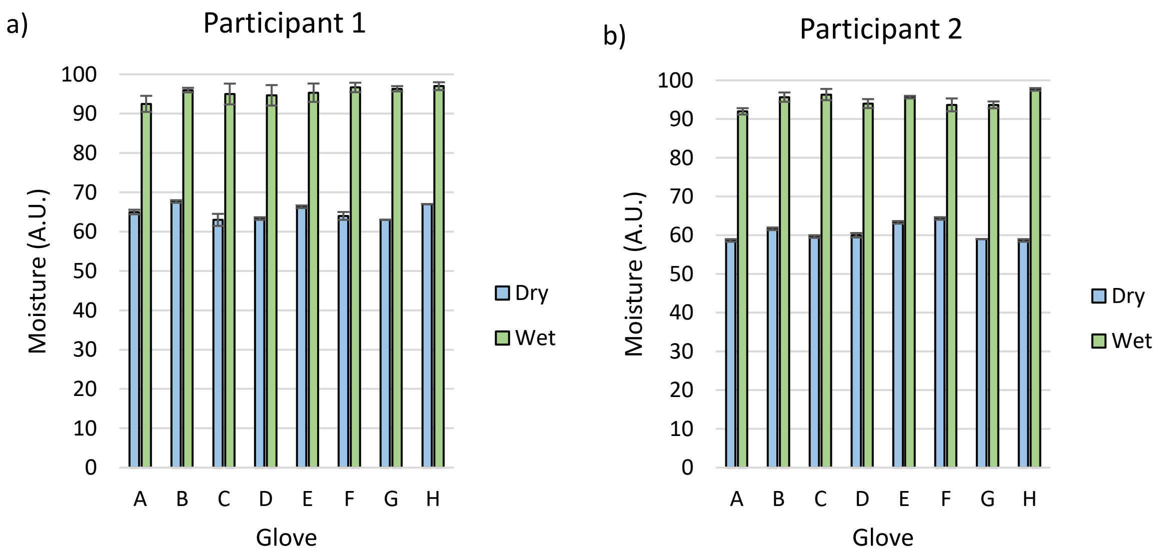


Figure 5.11. Correlation of stiffness at 100% strain with the preparation stage of the donning process in the dry condition. Thinner gloves are indicated by blue, and thick gloves by red.

5.4.7 Friction

Moisture

The results obtained from the moisture measurements for the friction tests are shown in Figures 5.12 a-c. In the donning test, the average results had moisture levels of 59.23 A.U. on average for the dry and 93.95 A.U. on average for the wet condition. The participants for the friction moisture show results similar donning moisture results. Paired t-tests between dry and wet conditions show the moisture content is statistically significant for each participant in each glove condition (*p<.001*).



c)

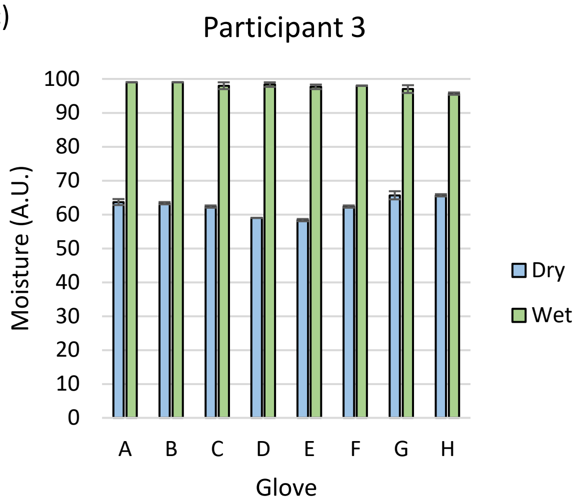


Figure 5.12 a-c. Results of moisture measurements for each participant in each glove test. Error bars denote standard error.

Glove-skin behaviour

The glove-skin behaviour was assessed in the first assessment of the friction, where the glove sample was attached to the force plate around the edges only, leaving the centre free to undertake relative movement. Many of the results obtained followed a typical friction graph, as seen in Chapter 4 (see Section 4.3.5). However, via this method, stick-slip and some sample stiffness contributed to the friction measurements. There are overall differences in the way the NBR reacts to the friction in both sets of thicknesses, and when moisture is added. This was mostly noticeable in the medium and high loads. Figures 5.13 and 5.14 show an example of the friction behaviour with one participant at 1 N with glove A (500ppm) and D (control) in the thinner gloves. In the chlorinated samples, the dry condition shows some ‘snapping’ of the NBR. The ‘snapping’ is defined as the glove being pulled with the finger, and then ‘snapping’ back into place, as shown in Figure 5.15. In the control, it can be seen that this snapping behaviour is more frequent, and in some participants, stick-slip also occurs. With the addition of water, the ‘snapping’ action worsens in these chlorinated samples, which can be seen from the friction graph on the right of Figure 5.14. When moisture is added in the unchlorinated sample, there are many more incidences of the snapping in combination with stick-slip. As observed, the finger would drag some of the glove, and when it snaps back, stick-slip would then occur, and then some of the glove would be pulled with the finger again. However, in the thicker samples, a slightly different behaviour is observed. In the dry condition, the gloves exhibit some of this snapping action, in combination with stick-slip (Figure 5.16). When moisture is added, there is more pronounced stick-slip with little of the ‘snapping’ action observed. No major differences are observed in the behaviour between the control and the chlorinated samples in the thicker gloves.

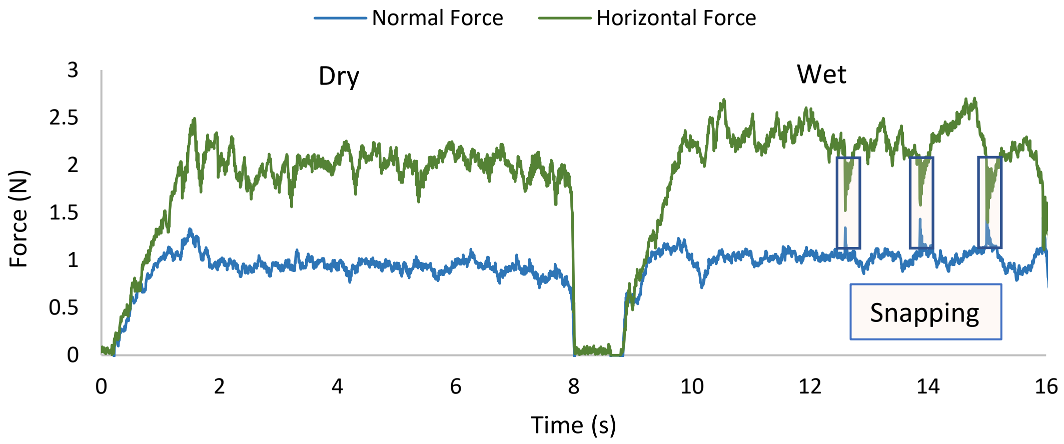


Figure 5.13. Friction graphs obtained from glove A (500ppm) in dry and wet conditions at the 1 N target load.

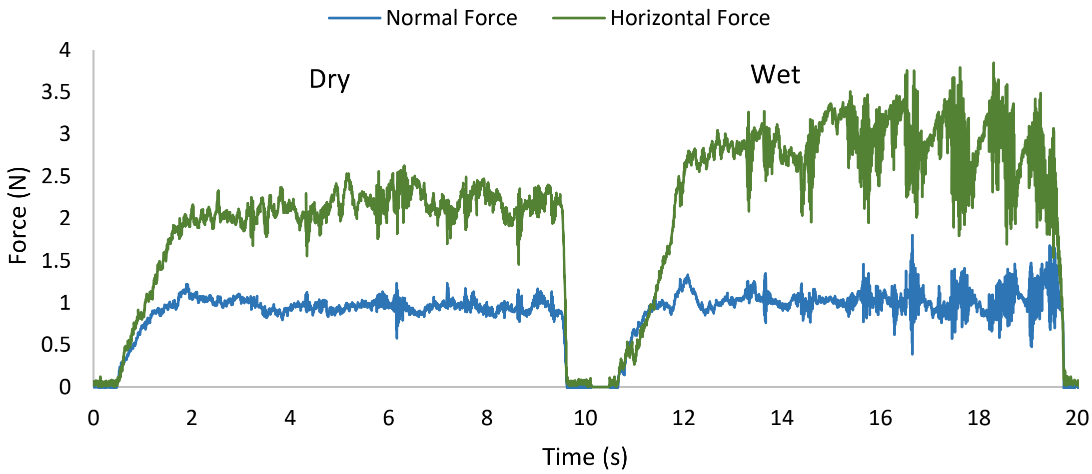


Figure 5.14. Friction graphs obtained from the thin control sample (D) in dry and wet conditions at the 1 N target load.

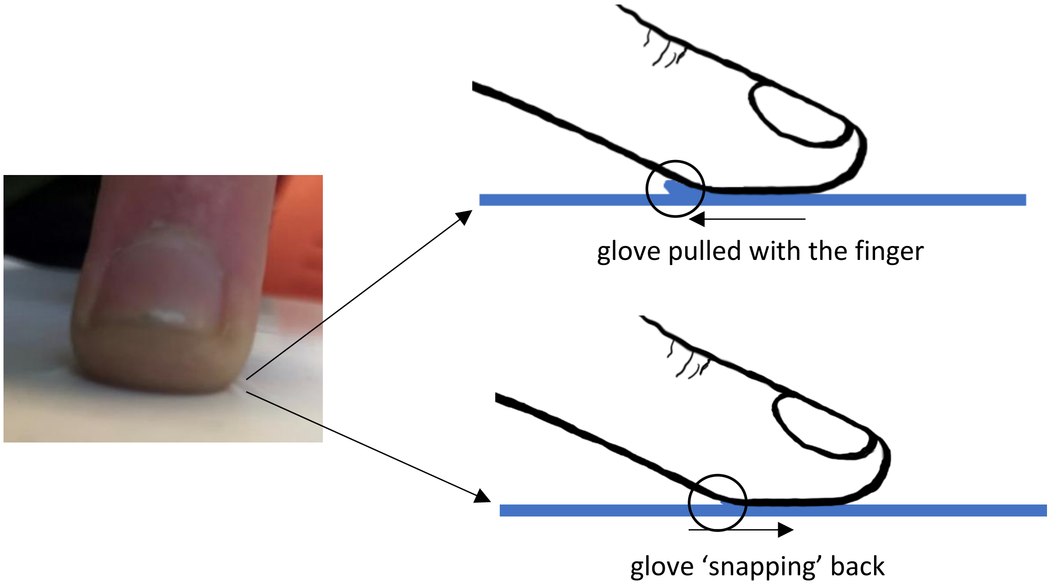


Figure 5.15. Glove stretching with finger and 'snapping' back.

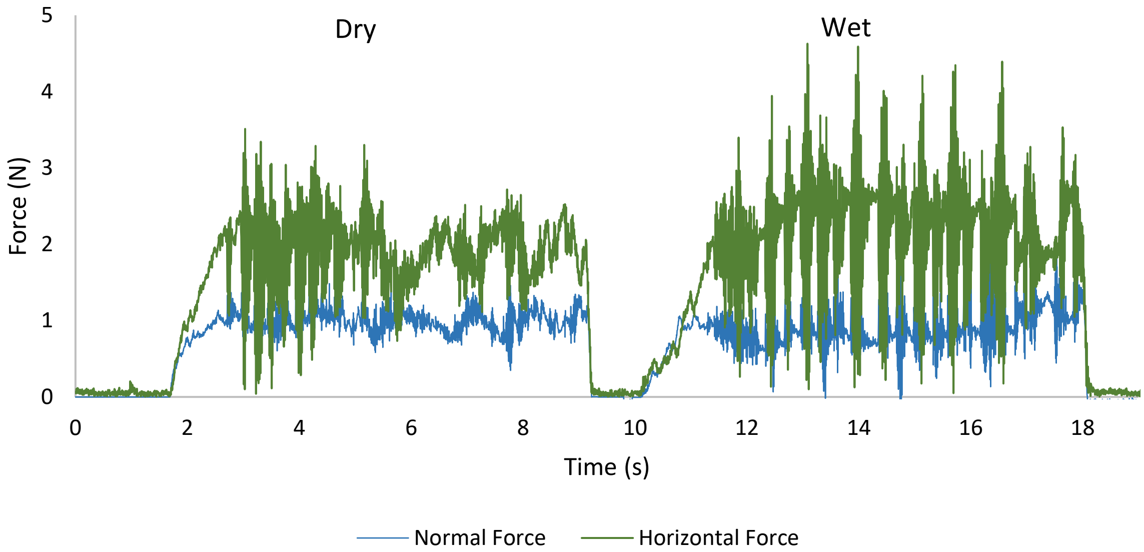


Figure 5.16. Friction graphs obtained from glove sample E (500ppm) in dry and wet conditions at the 1 N target load.

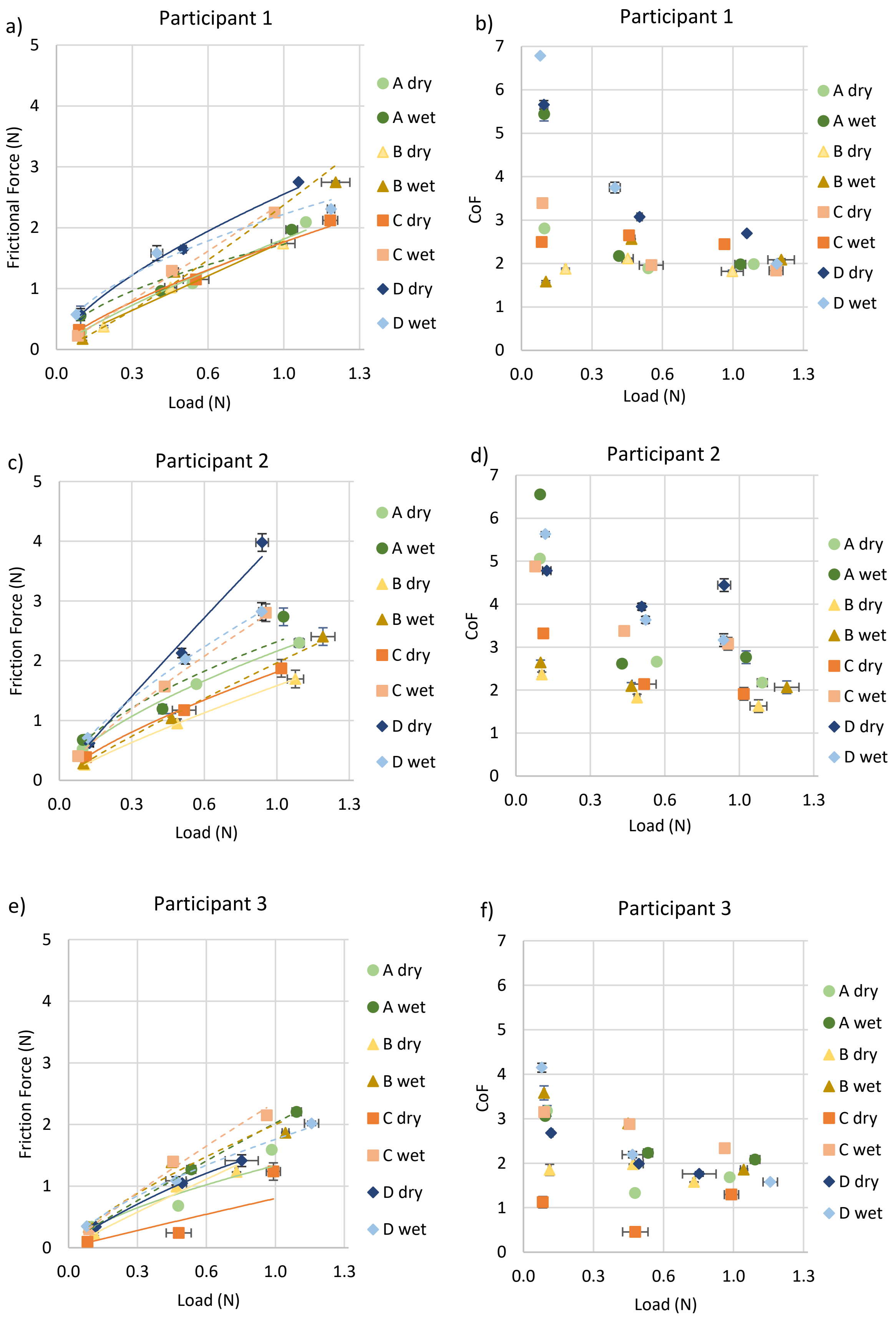
As the snapping action was occurring, this means there was relative motion of the glove across the force plate, thus CoFs calculated may not be an accurate measure of the skin-glove interaction, but rather the glove-force plate friction. Therefore, the experiment was repeated, with the glove section fully secured (with double-sided tape) to the force plate to prevent movement, as in Chapter 4.

Friction Coefficients

Where discussed, friction coefficients obtained for each participant are shown in the appendix (C2) with complete statistical analysis (C3-C5).

Thin gloves

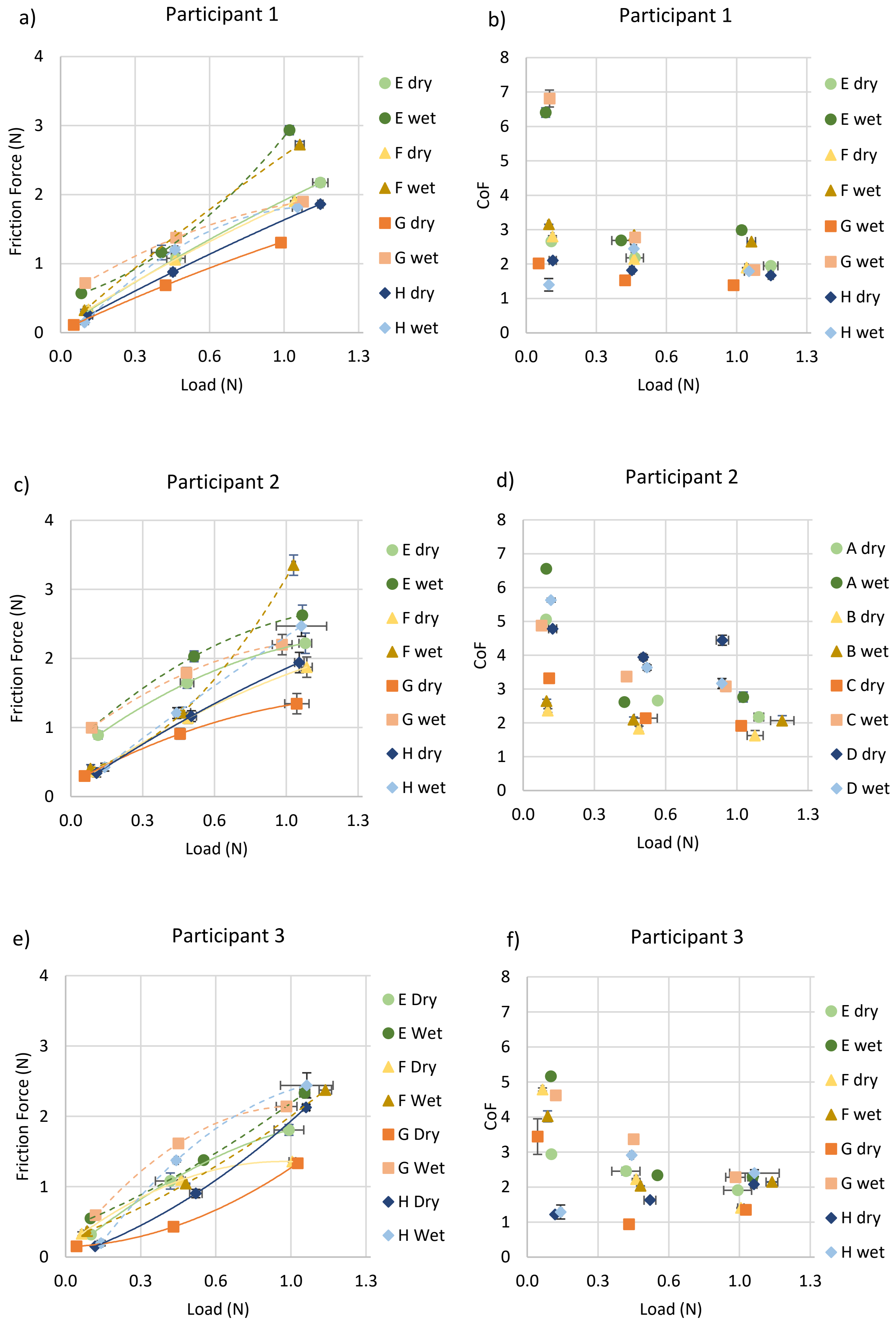
The average friction and CoFs at each normal load in the thinner gloves are shown in Figures 5.17 (a-f). In most of the participants, with all gloves, the CoF decreases as the load increases between the maximum and minimum target load. However, friction does increase with increasing target load. When moisture is introduced, the friction increases throughout the samples, in most instances. However, there are some exceptions to this, for example participant 3 at a target load of 0.1 N produces a dry CoF of 4.78 (±0.08) and a wet CoF of 4.02 (±0.01). Statistically significant differences are shown across all loads between the dry and wet conditions ($p<.05$). However, participants 2 and 3 show no significant differences in friction between wet and dry conditions in gloves A and D at the minimum load ($p<.05$). In the wet condition, glove D shows the highest friction at the minimum load with participants 1 and 2. Glove A (wet) shows a greater friction coefficient at the minimum load with participant 2. There is a slight trend that can be followed with the friction decreasing as chlorination strength is increased in the dry condition for participants 2 and 3. Overall, the control sample (D) has a greater friction coefficient, followed by glove A. Then B and C tend to have similar friction coefficients throughout the participants, with glove B generally lower than C, except in participant 3. No statistical difference is shown between B-C friction at the low and mid load in participants 1 and 2, following ANOVA and post-hoc Tukey's (HSD) tests ($p<.05$). The full statistical analysis (appendix C3-C4) shows that the most differences are highlighted between the D and gloves B and C at all loads in all conditions.



Figures 5.17 a-f. Average friction results from participants 1-3 with the thinner glove samples. Error bars denote standard deviation.

Thick gloves

The average friction and CoFs at each normal load in the thicker gloves are shown in Figures 5.18 (a-f). Friction increases with the increasing target load. As with the thinner gloves, when moisture is added, there is an increase in friction. Differences between dry and wet CoFs are shown to be significantly different ($p<.05$, appendix C3-C5). However, glove H in participant 3 shows no significant difference between the wet and dry conditions at the minimum (dry μ=1.22; wet μ=1.29; $t(2)=0.356$, $p=.756$) and maximum (dry μ=2.08 ; wet μ= 2.04; $t(2)=3.683$, $p=.066$) loads. Glove H is shown to have the lowest CoF when compared to the chlorinated gloves, followed closely by glove G at the medium and high loads. However, many of the loads show statistical differences between G and H across the participants ($p<.05$). When wet, there is little pattern in the results, as the gloves show different friction coefficients with the participants. As with the thinner samples, significant differences are shown frequently between the chlorinated gloves and the control sample ($p<.05$). In conjunction with this gloves F and G show frequent statistical differences from glove E ($p<.05$), but less frequent differences with each other ($p>.05$). Overall, across the participants, glove G, when the finger is dry, produces the lowest CoFs across the target loads. In the wet conditions, glove G gloves lower friction in participants 1 and 2, followed closely by glove F, which shows to produce lower friction with participant 3.



Figures 5.18 a-f. Average friction and CoF from participants 1-3 with the thicker glove samples. Error bars denote standard deviation.

Thickness differences

Paired t-tests show significant differences between thicknesses at the different loads. Participant one shows most of these differences, as each of the target loads produces a statistically different (*p<.05*) CoF between the thick and thin gloves. In general, the friction in the thicker gloves is slightly higher than those in the thinner gloves, with the exception of the control, which is significantly lower in the thicker gloves. In the thin gloves, the friction of the control (D) tends to be a higher friction at each load (in two out of the three participants), whereas in the thicker gloves, the friction for the control (H) is generally the lower. This difference in behaviour is highlighted in the t-tests, which show the majority of differences between gloves D and H being statistically significant (*p<.05*, appendix C3-C5). In both thickness sets the 2000 ppm (C and G) gloves show to produce the lowest CoF in the dry condition. However, when wet, the 1000 ppm (B and F) produces a the lowest CoFs. The thicker samples also showed stick-slip behaviour in some participants at the med/higher loads when moisture was added.

5.4.8 Friction correlation to donning

Both of the donning tests have shown that most variation is present in the 'hand insertion step', and this is where more friction occurs. Thus, this step has been explored in conjunction with the total donning time for each of the three participants taking part in the friction tests. Tables 5.12-5.14 show the Pearson correlation coefficients for each participant. The results show mostly moderate correlations between CoF and time taken in the wet condition. Much of this correlation is noted in the hand insertion step. However the stronger correlations are present in the total donning time. Participant 1 shows a moderate correlation in the wet condition to the time spend in the hand insertion step at the maximum load (*r=.621, p=.101*). On the other hand, the stronger correlations in participant 2 (Table 5.13) and 3 (Table 5.14) are noted in the total donning time. The strongest correlation coefficient for participant 2 is present at the minimum force (*r=.682, p=.063*), whereas the strongest for participant 3 is noted in the maximum force (*r=.699, p=.054*). None of the correlations had any statistical significance across the participants (*p>.05*). There is little in the way of pattern of behaviour in the correlation. However, it should be noted that glove E has a consistently high CoF with all participants and took the longer to don with participants 1 and 2.

Table 5.12. Correlation of CoF to total donning time and hand insertion step in participant 1.

Donning step	Condition	Min load (0.1 N)		Med load (0.5 N)		Max load (1 N)	
		r	*p*	r	*p*	r	*p*
Total	Dry	.532◊	*.175*	.115	*.787*	.070	*.870*
	Wet	.253	*.546*	-.141	*.740*	.568◊	*.142*
Hand insertion	Dry	.498Δ	*.209*	.145	*.732*	.075	*.859*
	Wet	.349Δ	*.397*	.117	*.783*	.621◊	*.101*

Δ Denotes a weak correlation. ◊ Denotes a moderate correlation.

Table 5.13. Correlation of CoF to total donning time and hand insertion step in participant 2

Donning step	Condition	Min load (0.1 N)		Med load (0.5 N)		Max load (1 N)	
		r	*p*	r	*p*	r	*p*
Total	Dry	.296	*.477*	.079	*.853*	-.115	*.786*
	Wet	.682◊	*.063*	.444Δ	*.271*	-.108	*.799*
Hand insertion	Dry	.160	*.704*	-.117	*.828*	-.294	*.480*
	Wet	.630◊	*.824*	.434Δ	*.282*	-.109	*.799*

Δ Denotes a weak correlation. ◊ Denotes a moderate correlation.

Table 5.14. Correlation of CoF to total donning time and hand insertion step in participant 3

Donning step	Condition	Min load (0.1 N)		Med load (0.5 N)		Max load (1 N)	
		r	*p*	r	*p*	r	*p*
Total	Dry	.143	*.736*	.638◊	*.088*	.699◊	*.054*
	Wet	.526◊	*.180*	-.216	*.607*	.127	*.764*
Hand insertion	Dry	.072	*.865*	.455Δ	*.257*	.698◊	*.054*
	Wet	.627◊	*.096*	-.221	*.601*	.069	*.871*

Δ Denotes a weak correlation. ◊ Denotes a moderate correlation.

5.5 Discussion

5.5.1 Physical properties

The results of the physical properties suggest that, in the thinner gloves, chlorination may have impacted the thickness, making the glove slightly thinner as the concentration of chlorine increases. The aim of the chlorination process is to chemically change the surface of the gloves, in order to improve the donning process and reduce tack (16, 198). These chemical changes may be the reason for the slight reduction in thickness. However, due to an incredibly small difference (±0.005mm), it is likely that this is a random result. Another difference is highlighted in the elongation at break of the different samples. In the thick gloves, the 500ppm sample has similar elongation at break to that of the control, which is statistically different from the 1000-2000ppm chlorination strengths. However, the results are similar, having no large differences in the elongation, with standard deviations overlapping. Thus, the differences may have some statistical significance, but the results are too similar to conclude that this is anything more than random, as statistical difference may have arisen as a result of the variation in the data, rather than any overall difference. Further work would have to be conducted to reveal any differences if present. The aim of this study was to compare gloves with the same manufacturing process and chemical constituents, with the exception of the treatment method, which has been achieved by the virtue of these physical property results.

Comparison of developed samples to industry

It is noted that there is some discrepancy between this data, and what is normally found within industry. When gloves are chlorinated, the polymers vulcanise and cross link (14, 38, 214). This lowers the tensile strength, elongation, force at break and modulus of the gloves. In effect, the chlorination process is detrimental to the gloves, decreasing their shelf life. However, in the gloves manufactured in this study, the detriment is not greatly reflected. In many cases, there is little difference in the physical properties when comparing the chlorinated gloves to the control sample. In the elongation at break, the control sample is shown to be significantly lower in the thinner gloves. The difference in the results here, in comparison to what is shown in the industry, may be down to the small-scale production. Gloves were dipped in batches for this study, whereas in manufacturing plants they are continuously on-line producing gloves, with hundreds of formers (14, 38, 51). This is all done successively, from the moment the former is dipped into the coagulant it follows a linear, timed process. However, in this small-scale production, the batches were dipped (two gloves at a time) and then left whilst other gloves were dipped. It is possible that the small-scale, room temperature/humidity and time left between dipping could have affected the properties of the gloves. It could also be that the chlorination method and time of chlorine exposure has contributed to the differences (16, 51, 52, 214). However it has been previously discussed by Karunaratne (51), that the chlorination method should not affect the process, as they all work in a similar way. It must also be noted, that more variation (standard deviation) is observed in the control samples in the thinner gloves. In the thicker gloves the sample with the highest physical properties is the control sample. Therefore, it is likely that the properties were affected by the chlorination as expected, but not as significantly as seen in the industry (16, 51).

The control sample is proven to be unexposed to the chlorination process via the results of the FTIR. The IR spectra shows that the control samples in this study have not been fully cured. The peak around 900cm^{-1} shows the H-C=C bending, which is not present in the chlorinated samples. In addition the thiol peak (H-S-H) is present in the control at ~2500 cm^{-1} (210, 215). These peaks strongly indicate that the vulcanisation is incomplete, and there are no sulphur cross links present. Without sufficient vulcanisation, the glove film tends to be softer. Consequently, the controls should have superior physical properties, which is observed in many of the physical properties. However, Tohsan, Joomcom, and Limphira (216) does show that the tensile strength of NRL gloves tends to decrease when the vulcanisation time is longer than 10 minutes due to the disulphide and polysulphide links created during the vulcanisation process. Therefore, it does seem there is some discrepancy between the processes used when manufacturing gloves on a small scale such as this, and a larger scale in industry, which slightly affects the properties of the end products.

5.5.2 Donning and friction

Size

All participants had stated they wear medium gloves as their 'best fit' size, hence their recruitment for this study as only medium sized gloves were manufactured. However, according to the HSE (149) chart for glove sizing, it was found that 2 participants were recommended to wear large while 3 were medium and 1 was small. There did not appear to be any visual issues with fit once the gloves were donned. Nor were there any comments around the fit of the gloves.

Chlorination Strength

The results of the donning process do not show statistically significant differences between the various glove chlorination strengths in the dry conditions. It was presumed that the controls (D and H) would take longer to don due to the increased friction from the 'tacky' surface, originating from the manufacturing process. However, this does not appear to be the case, which is likely to be a result of the powder being present. In both thicknesses, the 2000ppm (C, G) chlorination was quicker to don in the dry conditions, but the non-chlorinated gloves were quicker in the wet conditions. Only one significant difference was found to be present, which was between 500ppm concentration and the control in the thicker gloves when the hands were wet. As the control was faster to don, this suggests that chlorinating to 500ppm has an adverse effect on the donning process.

When correlating the donning to the friction, much of the correlations are present in the wet conditions, rather than dry, presumably due to similar incidences of the glove sticking to the skin across the participants. There is slight evidence that chlorinating to 2000ppm does improve the frictional properties and donnability of the glove in the thinner samples. For all participants glove C tends to be closer to the bottom of the correlation trendline (low friction and low donning time). However, the frictional properties of the thicker sample (G) were found to have a greater CoF and took longer to don. This would make it appear that there is some 'optimum' friction to aid the donning process, around the 1000-2000ppm region. Knowing the region of strength for optimal friction can be salient for manufacturers to improve glove user compatibility. However, the material parameters must be factored into the donning process. The difference in donning ability between the two gloves (C and G) is most likely to do with the difference in the physical properties of the two glove thicknesses and behaviour of the samples when donning.

Thickness

The thickness of the glove does appear to have affected the donning time, with the thicker gloves taking longer on average to don than the thinner gloves. Significant differences were observed between samples with the 1000ppm (B-F) chlorination strength (*p=.008*). This indicates that 1000ppm is the only chlorination strength at which gloves affect donning between the thicker and thinner gloves. This strength of chlorination is also shown to have the 'optimum' friction in the thinner gloves. This could be due to it being the minimum concentration to needed to reduce the anti-tack properties of the manufacturing process. The lack of statistical difference in the other results is likely to be due to the physical properties, and how these properties affected each step of the donning process. Firstly, participants spent less time on average in the 'preparation' stage with the thicker gloves. This is likely to due to the glove stiffness. The thicker gloves were shown to be stiffer than the thinner gloves. Therefore, these gloves were less likely to be subjected to creasing and folding when in the packaging, as shown in Figure 5.19. This means they did not require as much opening and mechanical separating as the thinner gloves. Furthermore, the ergonomics of easily gripping the cuff of the thicker samples is likely to be more streamlined, as the thinner gloves may be harder to grasp given less material being present. A possible way to circumvent these problems, is to make the cuff of the thinner gloves thicker, and therefore easier to grab. However, this will not solve the problem of the gloves being more creased due to packaging, which will cause issues with opening up the glove as well as sliding the fingers in, as discussed in Chapter 4, where the fingers experienced more sticking at the top of the palm and the base of the fingers.

Figure 5.19. 1) thicker glove (F); 2) thinner glove (B)

Secondly, the 'manipulation' of the gloves also differed between glove thicknesses. Where the thicker glove was donned, the rolling of the glove restricted the hand from being fully inserted and more time was added to unroll the glove. This was a by-product of the hand insertion step, where the glove moved easier down the fingers/hand in the thicker gloves but induced more rolling. In the thinner gloves, the glove was found to stick more to the fingers and participants spent time pulling at the fingers and pushing down at the top of the palm/joints of the fingers to ensure the glove fit, all of which was also noted in the previous work (Chapter 4).

The first friction test conducted, looking at the behaviour of the different samples, confirms there are differences in the way both the thick and thin glove sets react to the normal load. Furthermore, the correlation of mechanical parameters indicates that the stiffness of the material is an intrinsic part in the donning procedure. In the dry conditions, the thinner gloves exhibit more 'snapping', which is problematic when donning. It would appear, even though the skin is dry, there is some adhesion and/or the stiffness of the sample is allowing conformation and bending of the glove around the skin. When donning the gloves, this is likely to incur more incidences of sticking as the glove bends around the fingers, previously discussed in Chapter 4. This is much more problematic in the control gloves (D), in which stick-slip is then introduced. It is important to remember that glove D and H will have contained some powder residue from the manufacturing/former releasing process. It is possible that the powder may have been more present on the thicker gloves. However, the gloves were of a similar roughness (0.44µm and 0.49µm respectively). Thus, it is expected that the powder held onto the surface, however minimal, would be similar. Due to the similarity and frequency of the issues in the donning, there is little difference in the overall time taken to don the gloves of different thicknesses. Some participants commented that when donning the thicker gloves, the rolling had restricted their movement to the point that it caused some pain. This was noted only after they had donned the gloves and was not a level of pain where the participants did not wish to continue the study. This was noted more in the two participants who had a recommended fit of 'large' by the HSE (149).

Moisture

Across the total time taken to complete the three steps, wet hands were shown to significantly increase the time taken to don the gloves *($p<.05$)*. The only exception to this was glove F. Although, the wet hand condition took on average 5.77 seconds longer to don than the dry condition, no significance was found. Most variation is noted in the hand insertion step, which is to be expected as this is where most of the friction occurs between the glove and the skin. These findings were also touched upon in Chapter 4. In the thicker gloves, there is a visually smoother transition as the fingers slide down the gloves in the dry condition. However, when moisture is added, this step is slower, indicating stick-slip behaviour between the skin and the glove, which was confirmed in the friction results. The thinner gloves had a tendency to stick more to the hand, causing many issues whereby the participants had to pull harder on the glove and/or pull the glove away from the skin where the glove had stuck. Gloves C and G (2000ppm) had to have the greatest difference between the dry and wet conditions, increasing by 11.17 and 12.73 seconds respectively when moisture was present. This indicated that 2000ppm is more detrimental to the donning process when moisture is present. However, when dry, this appears to offer optimal friction and a quicker overall donning time. As the chlorination strength increases, the roughness of the surface decreases. In the dry condition this appears to aid the friction, but not necessarily the donning process, which is likely to be down to physical behaviour of the glove samples, as discussed. However, the smoother surface in the wet condition can cause more contact through capillary action and contact area, as discussed in Chapter 4 (see Section 4.6.1). Whilst it is clear that moisture adversely affects the donnability of the gloves, there is no clear indication that there is a strength of chlorination which aids or exacerbates this issue.

Surface roughness

The correlation of surface roughness to donning time suggests that the rougher the surface, the quicker the glove was to don. This is due to the rougher surfaces of the unchlorinated gloves D and H, pulling the trendline up, and indicating a greater correlation. The rougher surface could increase friction due to the gaps being filled by finger ridges as the surfaces move over each other (rough-rough contact), increasing asperity contact through an increase in surface area contact. Furthermore, when moisture is present, the water will flood these asperities, and cause capillary adhesion to the gloves. When the surface is smoother, as in the case of the 2000 ppm chlorinated samples, there appears to be a decrease the skin friction when compared to the 1000ppm samples. At 500-1000ppm, the smoother, but rougher than 2000ppm, surface is a little more detrimental, as evidenced through increased CoFs. This is due to several factors, but mostly the stiffness and behaviour of the samples under load, which leads to different skin-glove interactions.

5.5.3 Physical parameters

The elongation at break parameter has a weak correlation to donning when the hands are wet. This is likely suggesting that the less stiff the sample is (the more elongated it can ger), the more likely the glove is to conform to the fingers, causing issues with the glove adhesion to the skin when moisture is present. In conjunction with this, there is a weak correlation of the donning time to tensile strength. There is a statistically strong correlation between the sample stiffness and the tensile strength of the gloves observed in this study. This indicates that these properties are dependent upon each other, however more samples should be studied to conclude this. If this is a true correlation, this may allow for manufacturers to determine the donning capability and/or behaviour by assessing the tensile strength, as the tensile strength shows some correlations to the donning time, and stiffness also indicates correlation to the preparation stage. The correlations suggest that the stronger/stiffer the glove, the longer the glove takes to put on. Gloves chlorinated to 500ppm (A, E) and the thicker 2000ppm (C, G) have the highest tensile strengths, and highest hand insertion times, with respect to their thickness. The unchlorinated gloves (D, H) show the lowest tensile strength (for their respective thicknesses), and take the least time spent in the hand insertion step. This suggests that when the gloves are chlorinated to 1000ppm, the tensile properties formed in this glove allow for an easier donning process, as the hands spend less time in the 'hand insertion' step of the donning process. However, the 2000ppm glove is proven quicker to don overall, and has the lowest friction coefficients in the thinner gloves, further indicating the optimum chlorination strength is between 1000-2000ppm.

5.6 Conclusions

A summary of the findings from this chapter are shown in Table 5.15. The table shows the results of which gloves were quicker to don and compares the results of donning and friction with the wet hand condition to the dry condition. In all of the tests, the wet hand was shown to complicate the process and increase the time taken to don the gloves and increase friction.

Table 5.15. Findings of the chapter comparing the outcome of performance of the wet hand to the dry hand condition with comments on the quickest glove to don.

	Chlorination Strength (ppm)			
Measured parameter	**0**	**500**	**1000**	**2000**
Donning performance	Quickest to don when thicker	Greatest friction of chlorinated gloves	Quickest to don when wet	Quickest to don when dry
	Thin gloves (A-D)			
Donning Time	Increases	Increases	Increases	Increases
Friction	Increases	Increases	Increases	Increases
	Thick gloves (E-H)			
Donning Time	Increases	Increases	Increases	Increases
Friction	Increases	Increases	Increases	Increases

- Together with Chapter 4, a methodology has been designed to identify the complications of donning, and assess the ease of donning of gloves, as they are being donned in their natural state. This has allowed identification of how differences in gloves affect the donning process. The results of this protocol highlight four key stages of the process. Most variation and complication in this process is highlighted at the hand insertion step of donning a glove where the hand-glove system is more complex.
- Inclusion of moisture increases friction in all gloves, as seen with the previous study in Chapter 4. This is the same for all chlorination strengths, and the controls used in this study, showing no chlorination strength lessens the complexity of donning gloves with wet hands.
- When donning gloves it is clear that the skin-material friction is salient, which is dependent on the degree of chlorination, and the thickness of the material. In the thinner gloves, the chlorination is shown to aid the donning process through a decrease in surface roughness and friction. This decrease in friction is shown to be beneficial to donning in previous studies (57, 137). The thicker gloves, however, show a lower friction coefficient in the control, and the gloves were quicker to don. When chlorinating gloves, concentrations between 1000 and 2000ppm appear to be optimal, with a lower friction coefficient and quicker donning times observed in the dry conditions. Assessing chlorination strengths in between the 1000 and 2000 ppm may reveal a more optimum chlorination required for reducing friction with both dry and wet hands. However, the control gloves are easier to don than the chlorinated materials, with the thicker of the gloves showing a lower friction coefficient. This is likely to be due to the presence of powder, reducing the friction more than the chlorination.
- The bulk physical properties of the gloves should be accounted for when assessing the ease of donning gloves, not just the friction. Correlations have been shown between the stiffness of the material and the donnability. The internal coating/treatment is only discussed in previous literature. However, this study shows the complexity of the donning process requires a lot more consideration.
- Elongation at break and tensile strength are highlighted to be two of the mechanical parameters which require consideration during the manufacturing process. In particular, tensile strength shows statistically significant correlations to the material stiffness, which in turn shows correlations to the donning process at the preparation step. It is proposed that the stiffer glove samples bend and fold less in the packaging, which makes it easier to separate the two layers, and grab the cuffs to don the gloves. Material manufacturers should consider the effects these physical parameters have on the ease of donning, in order to improve the user

experience and increase compliance. However, more work should be conducted in this area in order to assess these correlations further.

- As noted in Chapter 4, there are issues amongst the sizes of gloves with some users. Gloves should fit well to the hand of the user, and the sizes measured in correlation with the glove users in this study, and the previous chapter, show some discrepancies. When donning, a smaller glove may suit the user by providing a better fit but is more difficult to don. A larger gloves would be easier to don, but may be loose around the fingers, which was a common complaint amongst glove users from the questionnaire in Chapter 3. Overall, there are clear issues highlighted between the best-fit of glove sizes and the recommended fits of the gloves, which requires further examination.

Chapter Six: Dexterity and friction

Dexterity was shown to be one of the highest reported issues amongst glove users in Chapter 3. Whilst it could be argued that gloves have been well assessed for dexterity in the literature, there are some issues present with these tests (6). The majority of studies assessing dexterity have attempted to differentiate glove performance by the use of the pegboard tests (6, 9, 12). However, as discussed in Chapter 2, the results of these studies give somewhat mixed results. Generally, the consensus in the literature is that medical gloves do not have a significant impairment on dexterity, although in some cases, there are observable differences in performance between gloves, or the bare hand. Many of the studies conducted on dexterity tend to compare two materials (normally NRL and NBR), with the hypothesis that one glove has a superior performance to the other. None of these studies, however, consider the material properties and the constituents of the gloves. Little work looks at why some gloves perform better than others. The aim of this chapter is to assess whether performance differences exist across similar glove materials with different properties. These properties could then be evaluated when manufacturing materials to predict what constituents and parameters may impact dexterity and friction. The novelty of this approach, in comparison to previous literature, considers the chemical differences between gloves of the same core materials, as well accounting for the physical parameters to assess gloves which have similar materials.

6.1 Introduction

As discussed in Chapter 2 and further highlighted in Chapter 4, manufacturing procedures, bulk raw materials, and treatment methods differ between gloves composed of the same material (such as NBR). These differences have been shown to affect the performance of donning in Chapter 4. No studies could be found assessing a range of gloves with known chemical and physical parameters. The differences between gloves materials are well known amongst glove users. NBR is stiffer and has a greater tensile strength than NRL, which gives it the perception of feeling thicker and hindering performance (7). However, linking these exact differences in properties to the performance has had little consideration. Two gloves made of NBR, for example, could be manufactured from different grades of acrylonitrile butadiene, and have different compounding agents, affecting the physical properties. Therefore, comparing dexterity across studies, where the same glove materials are used, may yield different results. Dexterity performance is commonly measured via the use of pegboard tests. The most frequent test encountered in the literature is the Purdue pegboard, as described in Tiffin and Asher [13] and discussed in Chapter 2. This test can be easily implanted into material manufacturing plants, and into the glove manufacturing plants for vital glove performance assessments and requires very little time to complete.

Furthermore, very little work has been shown considering the tribology of gloves and their effect on carrying out dexterous tasks. It is possible, that in the tests used, the actual dexterity is not affected as such by the gloves, but rather the introduction of a different surface contact into the system, which introduced tribological issues. Tribology plays an important role in the grip of the pins in studies of this ilk. Thus, without proper assessment of the tribology of gloves, it is difficult to determine whether the effects gloves have on dexterity are due to movement restriction or are a result of differences in friction, or a combination of the two.

6.2 Aim and scope

The aim of this chapter is to assess whether different gloves with different properties affect the dexterity of users. The novelty of this approach will consider the bulk material properties, as well as the chemical differences between the gloves. Furthermore, the tribological properties of the gloves will be assessed to understand the friction occurring between the glove films and the smooth metal components. The Purdue pegboard will be used to assess dexterity as it is a common test. Assessing whether there are specific properties which affect the tribological properties of the gloves, and the dexterity of glove users, will help inform glove manufacturers of the most important properties of the materials they are using. Additionally, this will inform raw material manufacturers how the chemical nature of the bulk raw materials affects glove properties, which in turn may affect tribology and consequently the ability of the wearer to carry out dexterous tasks.

6.3 Materials and methodology

6.3.1 Glove selection

The glove materials were chosen with the help of the Synthomer technical centre Sdn Bhd Kluang, Malaysia. The gloves were selected to reflect what is on the current glove market, available for purchase. Although rare, some exposure to the accelerants used in the NBR gloves can cause skin irritation amongst some users. However, there are NBR gloves which are manufactured without accelerants (162). To negate irritation by these chemicals used in NBR, PVC gloves are also used as alternatives where required. Although these gloves are not commonly used in the NHS, it is not obsolete, and is still used around the world (5). Thus, this study also incorporates the use of medical grade PVC for reference. The gloves used in this study are described in Table 6.1.

Table 6.1. List of gloves and known constituents.

Glove	Glove constituents
NBR 6348HS	Carboxylated acrylonitrile butadiene rubber made with Synthomer 6348HS. High level of acrylonitrile recommended for thinner gloves with superior break forces. Finished with chlorination treatment.
NBR 6329	Acrylonitrile butadiene rubber made with Synthomer 6329. Medium level of acrylonitrile recommended for thin gloves with greater tensile strength. Finished with chlorination treatment.
NBR 6311	Acrylonitrile butadiene rubber made with Synthomer 6311. Medium level of acrylonitrile recommended for softness. Finished with chlorination treatment.
NRL	Natural rubber latex, with stabilising agents and no bulking adulterants. Finished with chlorination treatment
NRL 10% filler	Natural rubber latex with 10% bulking adulterants added. Finished with chlorination treatment
PVC	Medical grade polyvinyl chloride. Finished with chlorination treatment.

6.3.2 Physical property measurements

The physical properties of the gloves were measured using a Tinius Olsen (TL-190) tensometer. Testing was carried out under the same EN standard testing conditions described in Chapter 4 (see Section 4.3.1). A total of 12 gloves of each set were analysed. The standards for testing were previously discussed in Chapter 4, stating gloves need to have a ≥6 N break force to pass. However, this is only true of natural and synthetic rubbers. Thermoplastics, such as PVC, have a lower break force tolerance at ≥3.6 N (59). The gloves were manufactured and then delivered to the Synthomer technical centre where they were tested. Therefore, the gloves were not left for a long time period prior to testing, which was noted as an issue in Chapter 4 whereby the physical properties decreased over time. Thickness was measured using a Mitutoyo micrometer (quick-mini, ± 0.01 mm) along the palm, finger, and finger pad, using the method stated in Chapter 4 (see Section 4.3.1).

Stiffness calculations

Stiffness has been calculated as with the gloves used in the Chapter 4. This was done using the formula given in Equation 4.1. Unless stated otherwise, the stiffness has been compared using the stiffness obtained at the lowest measured strain (100%) when assessing the modulus. In the donning Chapters (4 and 5), the stiffness around the 100% strain was likely more replicative of the conditions when pulling on a glove compared to the 300% and 500% stress. However, the strain of the glove, once on the hand, is likely to be much lower than 100%. Therefore, the strain used in these correlations may not be an accurate representation of the strain of a glove once donned on the hand.

Size measurements

Using a ruler, a total of ten of each of the gloves were measured for size across the palm, middle finger length and total length (middle finger-tip to cuff). This was the same procedure described in Chapter 4. In addition, the width of the fingers was also measured across the base of the middle finger.

FTIR

FTIR was conducted on the outer surfaces of the gloves to assess differences between the NBR gloves and the differences between the NRL gloves. This was to highlight any areas where chemistry may differ in the final glove products of the same bulk material. Analysis was conducted using a Brucker ATR-FTIR instrument. Each sample was scanned 26 times in the 550-4000 cm^{-1} region with a resolution of 4 cm^{-1}. Two sections of each glove were analysed and averaged by OMNIC software.

6.3.3 Task performance assessment

Dexterity was chosen to be a measure of performance for these gloves, due to it being a commonly reported issues in Chapter 3. The Purdue pegboard (Figure 6.1) was used for this study, as this is sometimes used in industry as part of a battery of standardized tests when evaluating newly designed gloves (12, 217). Furthermore, the test is easy to implement into the assessment process as it is not time consuming or a large piece of equipment. The test measures both gross and an element of finer dexterity and is comprised of a rectangular wooden board containing 25 holes running vertically both sides. The top of the board houses four concave dishes. The outermost dishes contain cylindrical metal pins, whilst the two central dishes house metal washers and collars. The test consists of four separate tasks, which are as follows:

- Left hand: total number of pins placed into the left column in 30 seconds, using only the left hand.
- Right hand: total number of pins placed into the right column in 30 seconds, using only the right hand.
- Both hands: total number of pairs of pins placed into the both the left and right columns at the same time, in 30 seconds.
- Assembly: total number of assemblies constructed. These assemblies consist of a pin-washer-collar-washer combination (as in Figure 6.2). The assembly of one structure had to be completed before moving onto the next. A total score was obtained from the parts of the structure assembled.

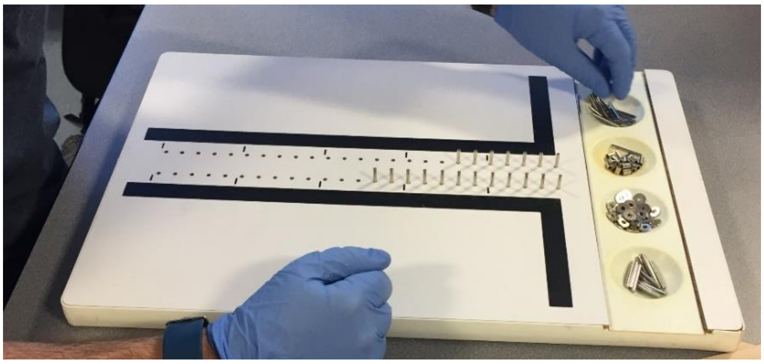


Figure 6.1. Purdue pegboard test

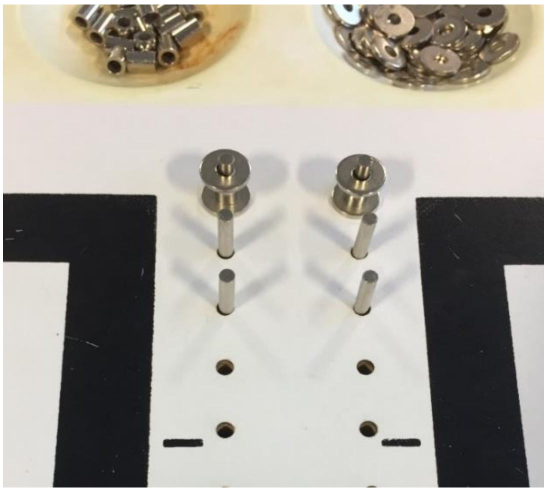


Figure 6.2. Assembly test construction

The test manufacturers recommend combining scores from all four tests to assess the results. However, it is deemed that as the pin placement tests are assessing dexterity on a grosser scale than the assembly test. Consequently, the tests were separated into the 'combined test' and the 'assembly test' with separate results recorded. In the combined test, scores are given as a total of the three 30 second pin placement tests, and the assembly consists only of the score obtained from the one-minute assembly test. Participants were instructed to not pick up any pins which were dropped in the test, as it was found these were difficult to grab and consumed a large portion of time. Any dropped pins/parts were counted. The total test combination was conducted in 7 gloving conditions, once with each of the glove films, and a bare (no-gloves) condition. Tests were carried out in the Human Interaction Group laboratory at the University of Sheffield with a room temperature range of 22-25°C and 50-57% humidity.

Participants

A total of 21 participants were recruited for the dexterity test. The gloves manufactured and donated by manufacturing companies for this project were of a "medium" standard size. This is said to be the most common size manufactured and sold in bulk by glove manufacturing companies. As this was the only size present, participants were selected based on their size preference being a medium. The participants were aged between 22-42 with no known sensorimotor conditions. Ethical approval was received by the Research Ethics Committee of the Department of Mechanical Engineering, The University of Sheffield (No: 016619/022735).

Hand size measurements

The hands of the participants were measured using the same method described in Chapter 4 (see Section 4.3.2). These were the same measurements recommended by the Health and Safety Executive (HSE) for sizing gloves for best fit to the hands (149). An additional measurement was taken in this study, which was across the base of the middle finger of both the participants and the gloves. Only the middle finger was arbitrarily chosen to save time. This was carried out due to the results of possible ill-fitting gloves noted in Chapter 4, where it was not considered if finger width could be a factor in hand insertion. Also, this measurement allowed for the assessment of any discrepancy between participants perceived best-fit size choice, and those published for recommendation of best-fit.

6.3.5 Friction methodology

The methodology for the friction analysis follows identically that described in Chapter 4 (see Section 4.3.4). A strip of steel (1.7 × 58 cm) was affixed to the AMTI plate using double sided tape, as in Figure 6.3. A surface profilometer (Mitutoyo, SJ400 ±0.01 µm) was used to determine the R_a of the steel surface. The surface was shown to have an R_a of 0.11 µm, a profile of which is shown in Figure 6.4.

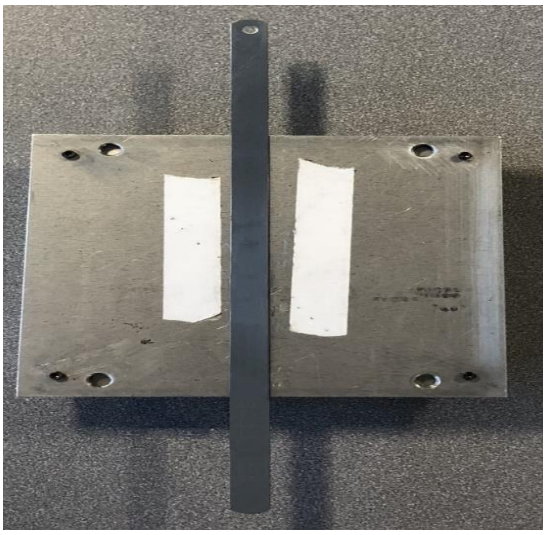


Figure 6.3. AMTI plate with steel strip attached.

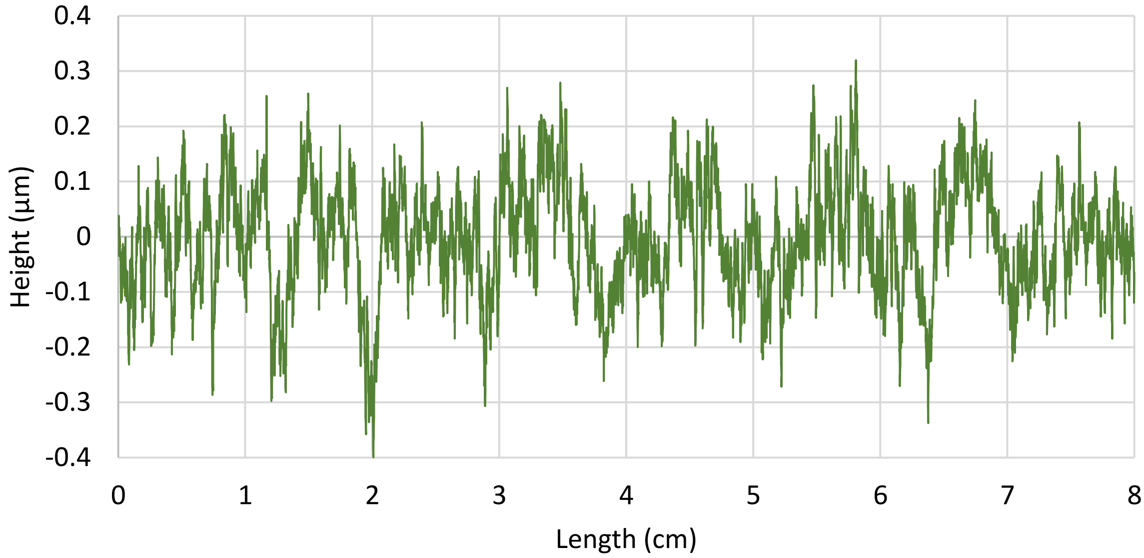


Figure 6.4. Surface roughness profile of steel strip.

A smooth steel was chosen as to represent the cylindrical metal pins used in the Purdue pegboard. In addition to this, the smooth metal surface is also representative of some of the commonly encountered surfaces (bedpans, trolleys, smoothed surface tools) discussed in Chapter 2 (see Section 2.6.3.). The angle between the finger and the surface was kept at approximately 40°, as with previous studies (57, 90, 104, 137), and held in contact with a near constant desired force as shown in Figure 6.5. The force was shown on a screen, and participants could see the force that was being applied. This allowed them to maintain a target force for each of the normal loads. Static friction was then measured by the sliding of the finger down the metal strip. Only static friction was measured for this study, as this is the friction most relevant in a medical setting (such as holding equipment and precision work) (114, 116). An example of how static friction is determined has been discussed previously (see Chapter 4, section 4.3.5). Gloves were donned on the right hand of the sole participant (male, aged 28). The friction tests were carried out with all six of the gloves and in a no-gloves condition.

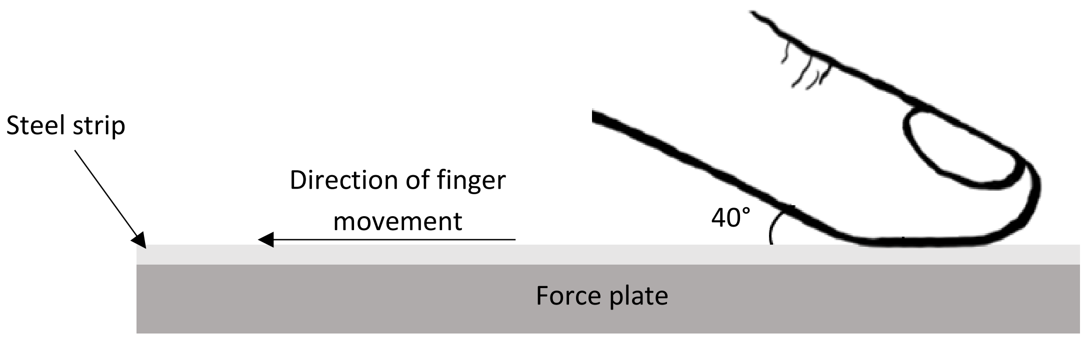


Figure 6.5. Schematic of friction test set-up.

Normal force selection

In preceding literature, loads of 0.3-40 N have been used to assess glove friction with varying surfaces (90, 113, 114, 116). As noted with the donning friction (Chapter 4), these studies rarely report why certain loads are selected. Forces of 1 N have been used in many studies looking at grip force, as it has been reported that this is the force used in precision grip (189). Therefore, the target loads selected in this study are 1, 2, 3, 4 and 5 N. As with the donning methodology in Chapter 4, this provides an understanding of how friction differs with normal load. Tests were repeated three times at each load to obtain an average.

6.3.6 Data analysis

As with the previous friction study, the resultant horizontal force was determined prior to the coefficient of friction (CoF) being calculated (equations 4.2 and 4.3). The data was then processed to a power fit law, also described in Chapter 4 (see equation 4.4).

Statistical analysis

The data was assessed for normal distribution following the Shapiro-Wilk test for normality (192). Where normally distributed, one-way ANOVA was conducted. Statistical significance is set at α=0.05. ANOVA was followed up with a post-hoc Tuckey's (HSD). Where non-normally distributed, the non-parametric Kruskal Wallis test was conducted, followed by the Dunn's multiple comparison test where relevant (195). The null hypothesis of the test states that there is no difference between the performance in both the Purdue tests, and the friction tests, across all glove conditions and the bare hand. Where a probability (p) of difference is $<.05$, the null hypothesis is rejected, and a significant difference is shown between results.

Correlation

Pearson correlation coefficients (r) were also calculated following the same regression analysis detailed in Chapter 5 (see Section 5.3.3). The regression analysis was used to assess for correlation between each measured physical property on the tensiometer to both the combined scores and the total assembly scores for each hand condition. In conjunction with this, as stiffness was found to correlate to the donning performance, the stiffness of the gloves was also used to assess whether correlations are shown to both the dexterity and the friction.

6.4 Results

6.4.1 Physical characteristics

The results from the physical characteristic testing are shown in Table 6.2, with the stress-strain curves shown in Figure 6.6. As the various grades of NBR are manufactured to create gloves with slightly different properties, obtaining gloves of the same film thickness is difficult, as many of the grade formulations are designed to create thinner gloves. The thickness (T) of NBR 3648 and 6329 are shown to be similar at 0.06 (±0.02) mm and 0.07 (±0.03) mm, respectively. However, the 6311 grade is slightly thicker at 0.10 (±0.05) mm. The thickness of the gloves is shown at the palm only, as is standard when recording glove thickness (59). Nevertheless, as discovered when measuring the gloves for donning in Chapter 4, it was noticed that the thickness slightly increased by around 0.01-0.02 mm towards the fingers. The gloves are shown to have slightly differing mechanical properties throughout. In the NBR gloves statistical differences are found between all NBR gloves in the break force (ANOVA $F(5, 66)=145.227, p<.001$. Table 6.3). No statistical differences are found between the NRL and NBR 6348HS ($Q=0.829$, $p=.900$), however, significant differences are shown between the other two grades of NBR, which are found to possess high break forces. Large differences are shown between the NRL and the NRL with 10% filler added. Break force (Fb) (Table 6.3), tensile strength (Ts) (Table 6.4), elongation (Eb) (Table 6.5), and stiffness (K) (Table 6.6) all show statistically significant increases when filler is added to the NRL. Significant differences are shown throughout all of the glove's stiffness following ANOVA ($F(5, 66)=975.567$, $p<.001$), with the exception of the NBR 6348HS (0.022 (±0.001) N/mm) and the NBR 6329 (0.020 (±0.001) N/mm) gloves ($Q=2.672, p=.419$). These two NBR gloves are also shown to have very similar properties with regards to other parameters. PVC, which is shown to have lower force at break, tensile strength and elongation was also found to be stiffest (0.065 (±0.004) N/mm), with the highest modulus of all of the gloves used.

Table 6.2. Physical properties of gloves.

	T (mm)	Fb (N)	Ts (MPa)	Eb (%)	K (N/mm)
NBR 6348HS	0.06 (±0.02)	6.33 (±0.31)	35.80 (±2.07)	514.25 (±9.74)	0.022 (±0.001)
NBR 6329	0.07 (±0.03)	7.01 (±0.74)	35.28 (±4.30)	565.83 (±9.15)	0.020 (±0.001)
NBR 6311	0.10 (±0.05)	8.88 (±0.91)	29.45 (±2.41)	496.58 (±17.33)	0.038 (±0.002)
NRL	0.10 (±0.03)	6.77 (±0.31)	20.17 (±0.94)	626.83 (±24.61)	0.013 (±0.002)
NRL (10% filler)	0.11 (±0.06)	9.12 (±0.52)	28.06 (±1.24)	837.58 (±35.95)	0.010 (±0.002)
PVC	0.07 (±0.03)	3.87 ±0.41)	18.64 (±0.96)	348.33 (±30.73)	0.065 (±0.004)

± denotes standard deviation

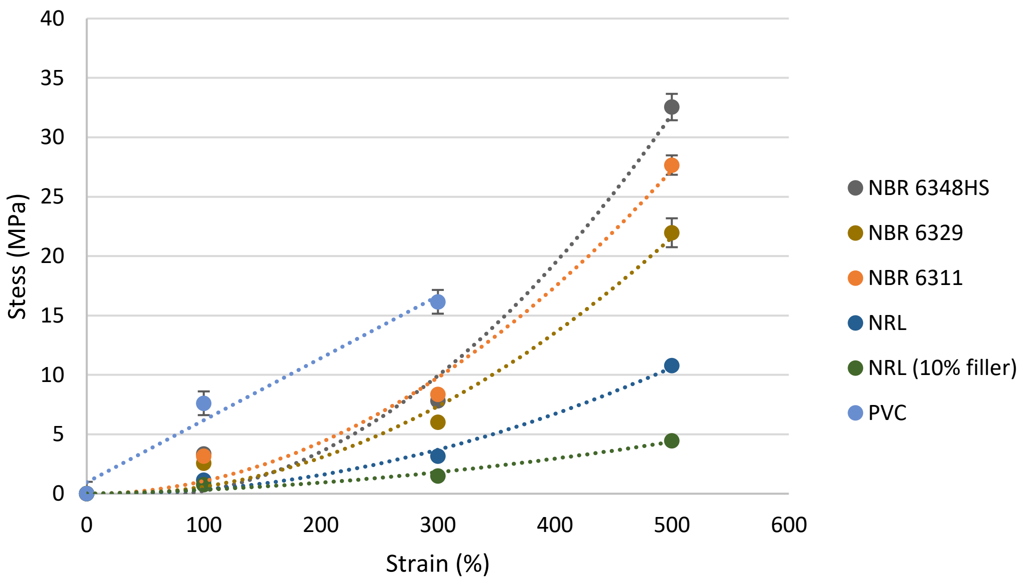


Figure 6.6. Stress-strain of gloves.

Table 6.3. Results of Tukey's (HSD) test following ANOVA (t(5, 66)=145.227, *p<.001*) on the force at break.

	NBR 6329	**NBR 6311**	**NRL**	**NRL (10% filler)**	**PVC**
NBR 6348HS	*Q=6.598 P=<.001**	*Q=17.805 P=<.001**	*Q=0.829 P=.900*	*Q=19.233 P=<.001**	*Q=12.266 P=<.001**
NBR 6329		*Q=11.207 P=<.001**	*Q=7.427 P=<.001**	*Q=12.636 P=<.001**	*Q=18.863 P=<.001**
NBR 6311			*Q=18.634 P=<.001**	*Q=1.428 P=.900*	*Q=30.071 P=<.001**
NRL				*Q=20.062 P=<.001**	*Q=11.437 P=<.001**
NRL (10% filler)					*Q=31.499 P=<.001**

** denotes statistically significant differences (p<.05).*

Table 6.4. Results of Tukey's (HSD) test following ANOVA (t(5, 66)=635.368, *p<.001*) on the tensile strength.

	NBR 6329	**NBR 6311**	**NRL**	**NRL (10% filler)**	**PVC**
NBR 6348HS	*Q=0.786 P=.090*	*Q=9.571 P=<.001**	*Q=23.494 P=<.001**	*Q=11.629 P=<.001**	*Q=25.800 P=<.001**
NBR 6329		*Q=8.786 P=<.001**	*Q=22.709 P=<.001**	*Q=10.844 P=<.001**	*Q=25.015 P=<.001**
NBR 6311			*Q=13.923 P=<.001**	*Q=2.058 P=.670*	*Q=16.229 P=<.001**
NRL				*Q=11.865 P=<.001**	*Q=2.306 P=.571*
NRL (10% filler)					*Q=14.171 P=<.001**

** denotes statistically significant differences (p<.05).*

Table 6.5. Results of Tukey's (HSD) test following ANOVA (t(5, 66)=573.568 *p<.001*) on the elongation.

	NBR 6329	**NBR 6311**	**NRL**	**NRL (10% filler)**	**PVC**
NBR 6348HS	*Q=7.594 P=<.001**	*Q=2.601 P=.450*	*Q=16.574 P=<.001**	*Q=47.598 P=<.001**	*Q=24.426 P=<.001**
NBR 6329		*Q=20.195 P=<.001**	*Q=8.980 P=<.001**	*Q=40.006 P=<.001**	*Q=32.019 P=<.001**
NBR 6311			*Q=19.175 P=<.001**	*Q=50.201 P=<.001**	*Q=21.825 P=<.001**
NRL				*Q=31.026 P=<.001**	*Q=41.000 P=<.001**
NRL (10% filler)					*Q=72.025 P=<.001**

** denotes statistically significant differences (p<.05)*

Table 6.6. Results of Tukey's (HSD) test following ANOVA (t(5, 66)=975.567, *p<.001*) on the calculated stiffness at 100% strain.

	NBR 6329	**NBR 6311**	**NRL**	**NRL (10% filler)**	**PVC**
NBR 6348HS	*Q=2.672 P=.419*	*Q=24.432 P=.001**	*Q=13.234 P=.001**	*Q=18.069 P=.001**	*Q=65.533 P=.001**
NBR 6329		*Q=27.104 P=.001**	*Q=10.562 P=.001**	*Q=15.397 P=.001**	*Q=68.206 P=.001**
NBR 6311			*Q=37.666 P=.001**	*Q=42.501 P=.001**	*Q=41.102 P=.001**
NRL				*Q=4.836 P=.013**	*Q=78.767 P=.001**
NRL (10% filler)					*Q=83.603 P=.001**

** denotes statistically significant differences (p<.05)*

6.4.2 FTIR

NBR

The FTIR spectra for the NBR gloves are shown in Figure 6.7. NBR 6311 and 6329 show very similar spectra, except in the 1575-1540cm^{-1} region. This absorbance corresponds to the carboxylate group (COO^-), which is not present in the NBR 6311 gloves. The presence of the carboxylate may be masked in the 6311 by the inclusion of stabilisers and materials used to compound the NBR. The most dissimilar of the three gloves is the 6348HS grades. There is strong peak absorbed by the 6348HS material at 3690cm^{-1}, which are not present in the other gloves. This peak corresponds to silanol groups (Si-OH). This strongly indicates that this glove was finished with a silica dip or silica has been used in the compounding process. Further differences between the 6348HS grade and the other gloves are highlighted by peaks being present in 6348HS around 1055-1010cm^{-1}. These correspond to Ester (O=C-O) stretching or aliphatic amine (C-N) bending (209, 210). Differences are expected, due to the gloves being manufactured by different companies, using different processes, and different preparation techniques. Changes in the crosslinking, degrees of crystallisation of the polymers and polymer chain orientation are all factors which can contribute to slight differences in the spectra between absorbance with different functional groups (209).

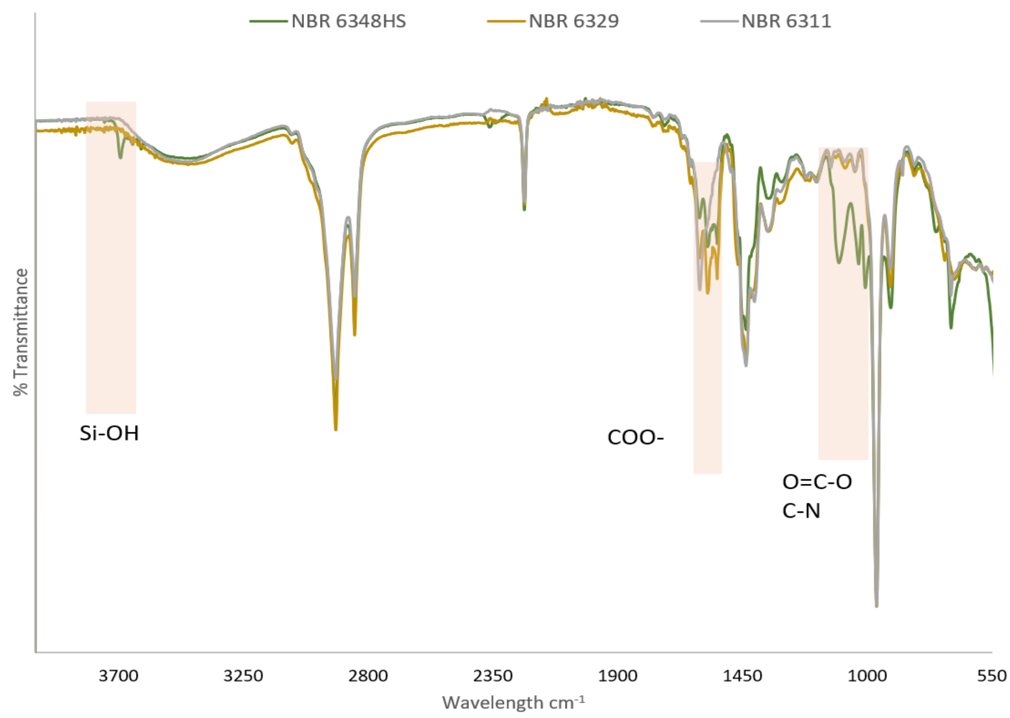


Figure 6.7. FTIR spectra obtained from NBR gloves. Differences are highlighted in red.

NRL

The NRL gloves are shown to be very similar from the spectra, shown in Figure 6.8. Although no great differences are present in the spectra, absorbance is noticeably lower in the glove which has had adulterants added. More absorbance, however, is noticed in the hydroxyl (OH) region between 3550-3200cm^{-1} (210). This is showing that the added adulterants could have slightly decreased the absorbance, likely due to less presence of the natural rubber. Although, the results do show no great differences are present in the overall spectra between the chemical structures of the different gloves. It is possible that there are slight differences further down the spectra (>500cm^{-1} region), but as the region (1500-500cm^{-1}) has strong similarities in spectra, it is likely the bulking agents have not changed the overall chemical structure of the glove. As stated with the NBR, the difference in the polymer chains can cause slight changes in absorbance between spectra.

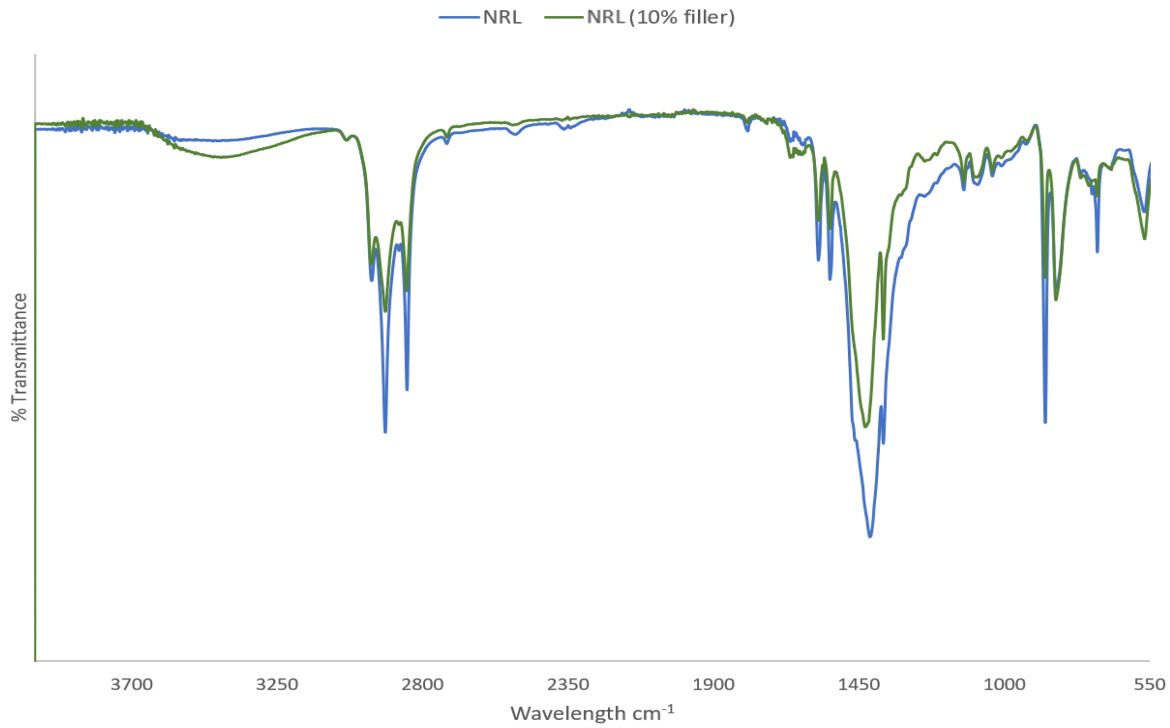


Figure 6.8. FTIR spectra obtained from NRL gloves and NRL gloves with filler.

6.4.3 Glove and hand size

Glove size

The glove measurements are shown in boxplots showing glove/hand length (Figure 6.9), finger length (Figure 6.10), palm span (Figure 6.11) and finger width (Figure 6.12). These plots show the range of data (indicated by the error bars), the median indicated by the line in the interquartile box range and the mean represented by the cross. Additional data points are shown as outliers, which deviate from the normal distribution within the data. There are some small variations noted between the gloves. Most difference is present in the glove length, where the largest difference is between PVC (23.32 ±0.11 cm) and NBR 6311 (24.91 ±0.20 cm). Slight differences are observed in the finger length also, where the NBR 6329 gloves shows to be slightly longer at 7.69 (±0.07) cm, whilst the other gloves range from 7.50-7.68 cm. When the gloves were donned, they were inspected for fit prior to the experiment being conducted. No great visual issues were present. However there was a little excess material noted in some participants with NBR 6329 and the PVC gloves in some participants. In the NBR 6329, the excess was noted at around the tip (finger length= 7.69 ± 0.07 cm), whereas in the PVC, the excess was noted around the base of the fingers (finger length = 7.61 ± 0.10 cm). However, this was not excessive and was not indicative of an incorrect size being used (e.g. a smaller size would have been tight around the palm and possibly the fingers).

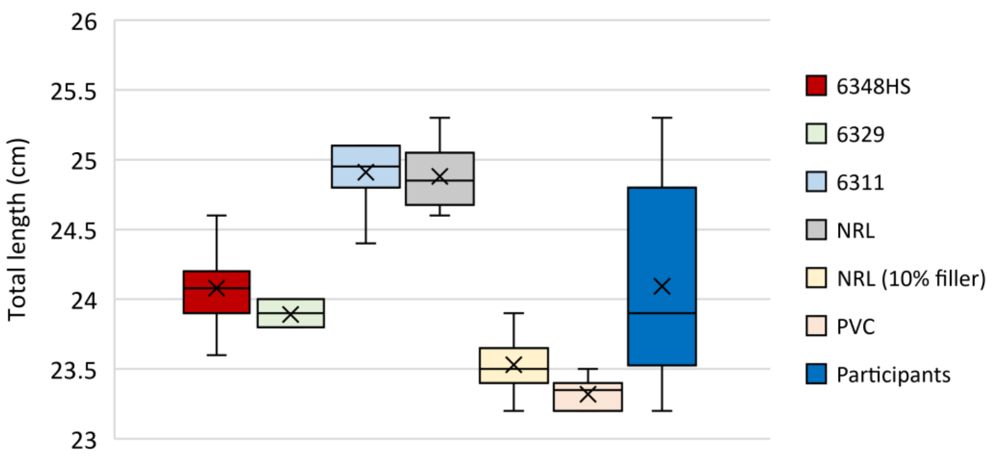


Figure 6.9. Comparison of the length of gloves used and the length of the participants' hands.

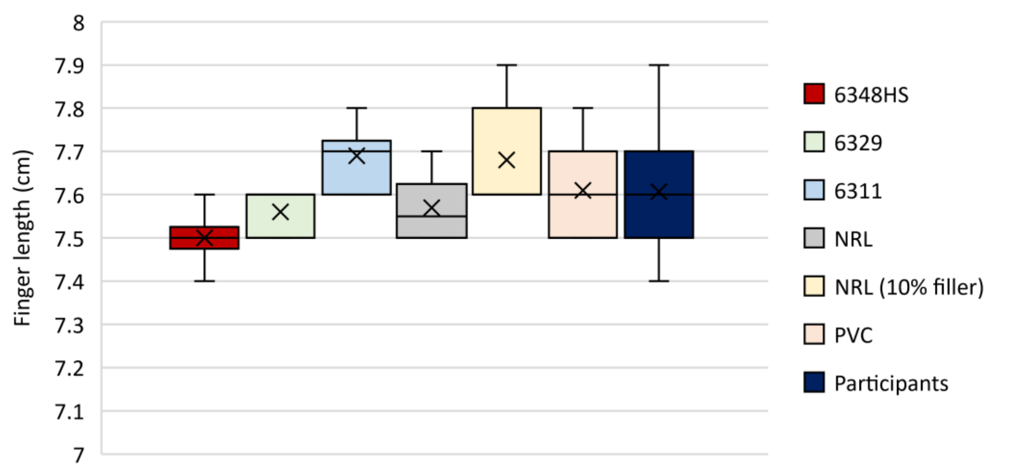


Figure 6.10. Comparison of the length of middle finger of the gloves used and the length of participants' middle finger.

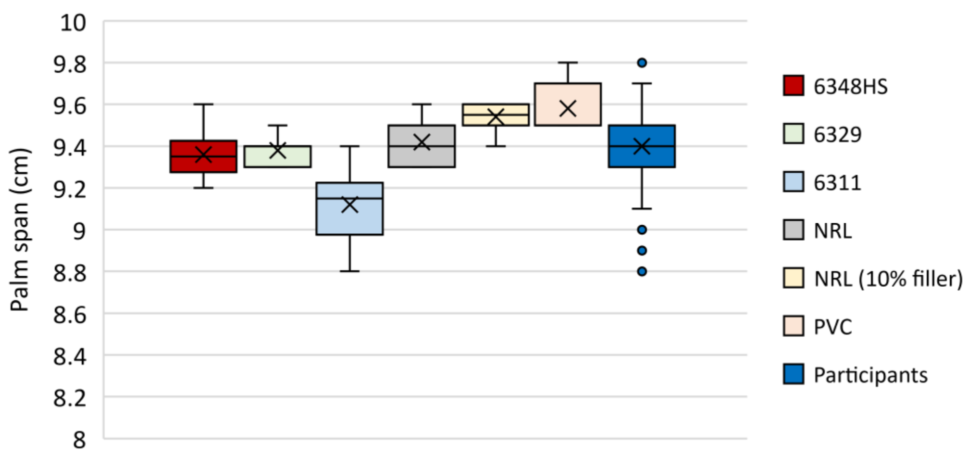


Figure 6.11. Comparison of the palm span of the gloves used and the span of the participants' hands.

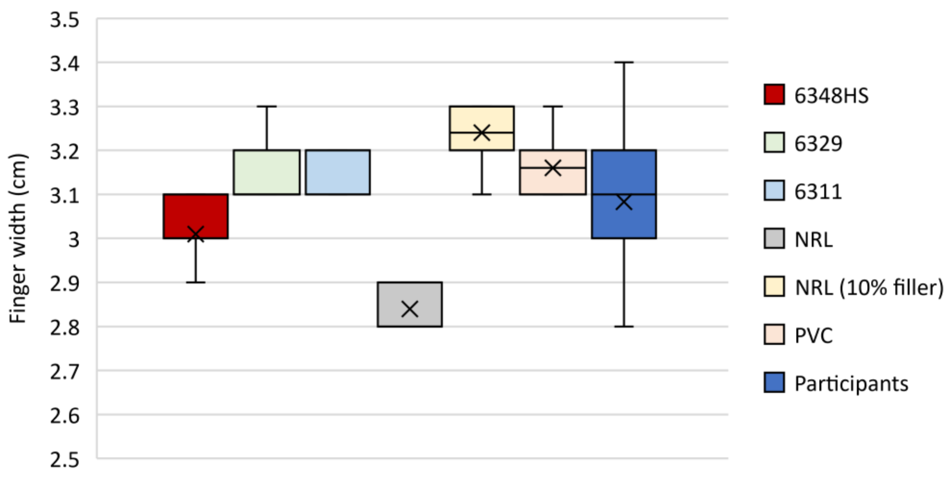


Figure 6.12. Comparison of the finger width of the gloves used and width of the participants' index fingers.

Participant sizes

As is clear from the results presented in Figure 6.9-6.12, there are differences between the glove sizes, and the participant hand sizes. However, these size differences are marginal in most cases. The length of the total glove is larger than the participant's hands. However, this is normal, as the glove measurement includes the cuff, which tends to cover the wrist. The most important sizes pertain to the palm span, finger length and finger width. A larger palm span is observable in the participants, with a much greater variation. The average lengths of the fingers show similar measurements throughout the gloves and the participants. The NBR 6311 shows the largest deviation from the participant's average (NBR: 7.69 ± 0.07 cm; participants: 7.61 ± 0.13 cm). Most variation is shown in the finger width, where the NBR 6829, 6311, NRL with filler and the PVC have greater width. However the difference between the averages is minimal. Comparisons of this nature must be approached with caution when interpreting, as the gloves are measured when flat. Therefore, it may appear that the measurements are likely to be different between the gloves and the participant hand sizes, however these measurements do not account for the geometry of the glove expansion once the hand is inside.

The hand measurements taken were compared to the HSE size gloving chart (149). All participants had at least one hand measurement that aligned with that to recommend a 'medium' glove sizing. Of the 21 participants, only 4 had a finger length and palm circumference which both aligned with the medium size category (Figure 6.13). Of the remaining participants, a total of 13 participants had a recommended palm circumference, and 4 had a recommended finger length as appropriate for medium glove sizing.

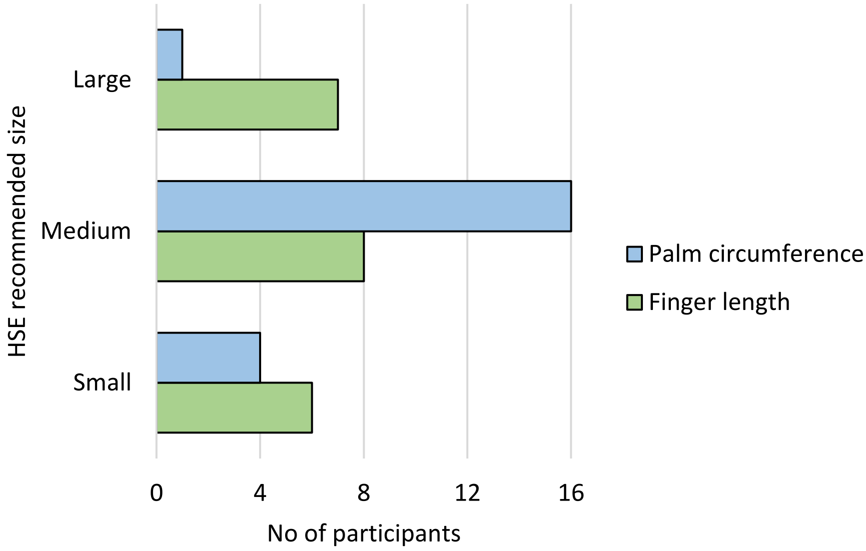


Figure 6.13. Distribution of recommended glove sizes amongst the participants based on palm circumference and finger length measurements.

6.4.4 Dexterity

Combined

The results of the combined test are shown in Figure 6.14. Scores have been normalised to show the differences in gloved score to the bare hand condition (gloved score – bare hand score). As the data was found to be non-parametric, the Kruskal Wallis test was conducted, which shows significantly different results across the conditions (*H(6)=41.014, p=<.001*). All gloves are shown to significantly reduce performance, with a lower number of pins placed when compared to the bare hand following the Dunn's test (*p=<.001*, Table 6.7). However, the difference between some of the results is not large. For example, when the NRL with filler was worn, the score was an average of 42.5 (±5.90), NBR 6348HS with an average of 42.10 (±5.82) and the bare condition an average of 46.14 (±5.60). The bare hand also showed less pins being dropped, with only 5 people dropping pins, and only 6 pins were dropped across the entire tests (0.42 pins on average, Table 6.8). Across the NBR gloves, the 6311 grade scored the lowest when donned, across all participants, with an average score of 37.71 (±5.90). Only one significant difference is noted between participants with the NBR gloves, which is between the 6311 and the 6348HS grades (*Z=2.015*, *p=.022*). Although the dexterity performance was not as good as when the 6348HS glove was worn, the 6329 glove showed the least pins dropped, with only 7 participants contributing to dropping 11 pins (0.52 on average). In the NRL gloves, the difference in scores when these two gloves are donned is not significantly different. However, the NRL which included filler allowed the participants to perform better than when the other gloves were donned. When the PVC glove was donned, performance was worse than any of the other gloving conditions, and on average, 2 pins were dropped per person.

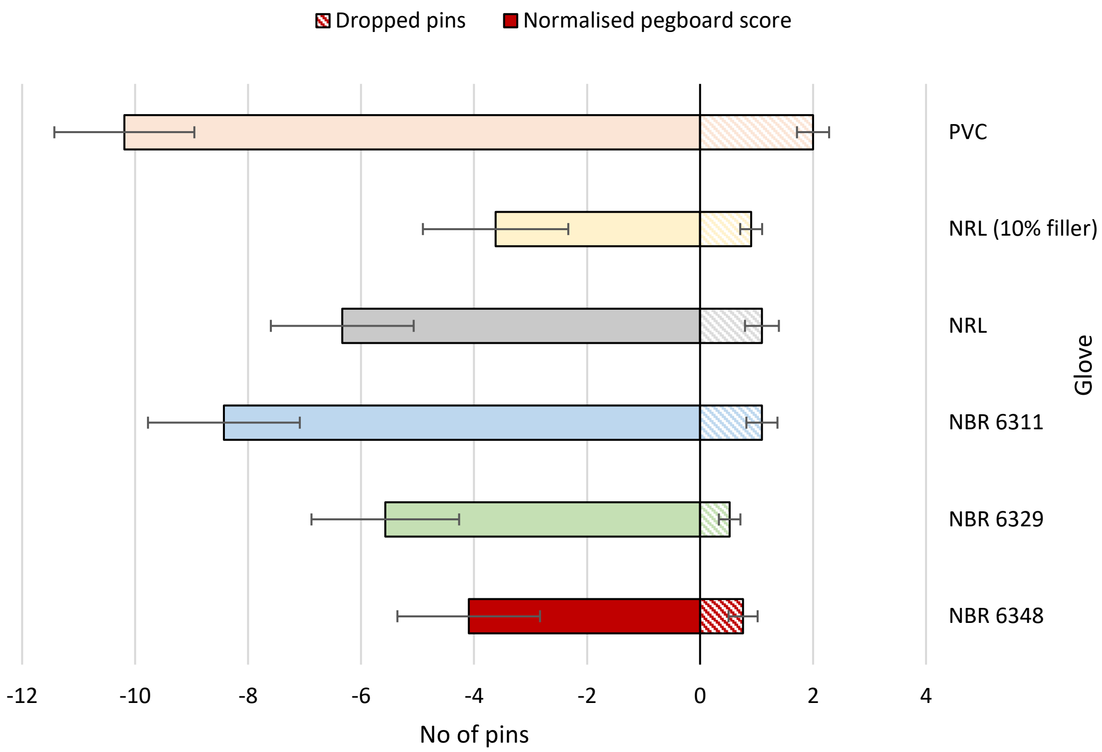


Figure 6.14. Normalised results (gloved score – bare hand score) of the combined test (left hand, right hand and both hands) in the Purdue Pegboard test. Error bars denote standard error.

Table 6.7. Post-hoc Dunn's test results conducted after Kruskal-Wallis on combined test scores (H(6)=11.014, *p=<.001)*.

Glove	NBR 6348HS	NBR 6329	NBR 6311	NRL	NRL (10% filler)	PVC
No gloves	*Z=3.090 p=<.001**	*Z=3.076 p=<.001**	*Z=2.346 p=<.001**	*Z=3.090 p=<0.001**	*Z=2.978 p=<.001**	*Z=2.652 p=<.001**
NBR 6348HS		*Z=0.028 p=.511*	*Z=2.015 p=.022**	*Z=0.665 p=.253*	*Z=0.048 p=.519*	*Z=3.174 p=<.001**
NBR 6329			*Z=0.048 p=.104*	*Z=0.327 p=.628*	*Z=0.867 p=.193*	*Z=3.317 p=<.001**
NBR 6311				*Z=0.066 p=.254*	*Z=2.748 p=.003**	*Z=0.533 p=<.297*
NRL					*Z=1.447 p=.074*	*Z=1.896 p=.029**
NRL (10% filler)						*Z=3.115 p=<.001**

** denotes statistically significant differences (p<.05)*

Table 6.8. No of pins dropped in the combined test.

Glove	Pins dropped	No of participants who dropped pins	Average
No gloves	6	5	0.29
NBR 6348HS	16	10	0.76
NBR 6329	11	7	0.52
NBR 6311	23	13	1.10
NRL	23	13	1.10
NRL (10% filler)	19	13	0.91
PVC	42	18	2.00

Assembly

The results of the assembly test are shown in Figure 6.15. As with the combined test, the scores have been normalised (gloved score – bare hand score) to compare dexterity to the bare hand condition. As fewer pieces were assembled on average when compared to the no-gloves condition, this shows that dexterity was impaired with all gloves. The Kruskal-Wallis test was conducted due to non-parametric data, which shows statistically significant differences between the glove conditions ($H(6)=31.241$, $p=.001$). Table 6.9 shows the results of the post-hoc Dunn's test, which shows significantly less pins were placed when NBR 6311 (27.86 ±5.19), NRL (30.62 ±7.16), and PVC (25.10 ±4.66) are compared to the bare hand condition (35.57 ±5.97) ($p<.05$).

In the NBR gloves, the participants wearing the 6311 grade performed significantly worse than when the 6329 (32.52 ±6.01, $Z=2.067$, $p=<.018$) and the 6348 (31.86 ±6.37, $Z=1.774$, $p=.038$) gloves were worn. A superior performance is observed when the adulterated NRL (32.52 ±6.98) was worn, when compared to the unadulterated NRL (30.62 ±7.16). As with the combined test, performance was lowest with the PVC glove, which is statistically significant across all glove conditions ($p<.05$), except with the NBR 6311 ($Z=0.726$, $p=.234$) gloves. The number of parts dropped was higher when the PVC glove was worn, with 3.1 parts dropped on average. Across 12 of the participants, 29 parts were also dropped when the 6311 NBR glove was worn (average 1.38 across all 21 participants), as displayed in Table 6.10. In the gloved conditions, the least amount of dropped pins was observed when the adulterated NRL gloves were worn, which showed an average of 0.43 parts dropped. It was also noted that participants knocked off the top washer in the already assembled parts when completing other assemblies. Participants were asked to ignore the washers that had been knocked off and were counted as complete assemblies. The knocked off washers were counted and are also shown in Table 6.10. It is shown that the when the PVC gloves were donned, 1.76 parts were knocked off on average, whereas when the NBR 6348HS and adulterated NRL were donned, only 0.22 washers were knocked off on average. In comparison to the bare hand condition, gloves appear to incur this knocking off of washers, as only one participant knocked one washer off over the course of the tests in the bare hand condition.

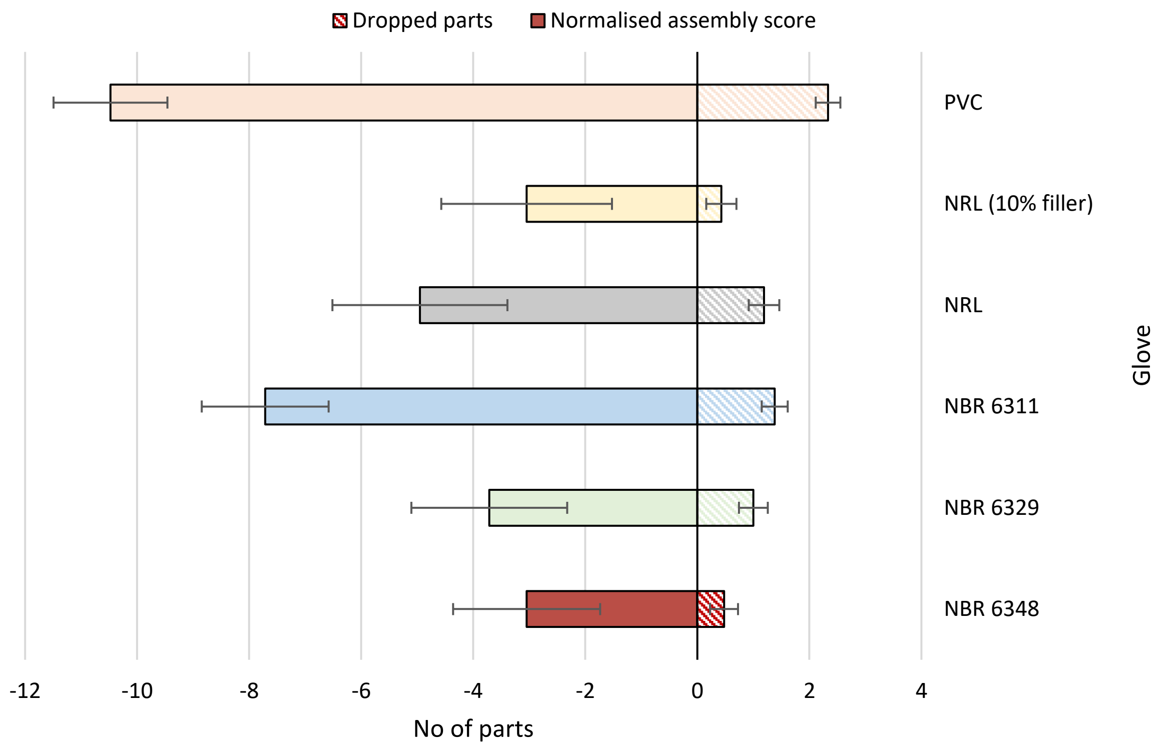


Figure 6.15. Normalised results (gloved score – bare hand score) of the assembly test of the Purdue Pegboard test. Error bars denote standard error.

Table 6.9. Post-hoc Dunn's test results conducted after Kruskal Wallis on assembly test scores (H(6)=31.241, *p*=<.001).

Glove	NBR 6348HS	NBR 6329	NBR 6311	NRL	NRL (10% filler)	PVC
Bare	*Z=1.911 p=.208*	*Z=1.70 p=.121*	*Z=3.163 p=<.001**	*Z=1.943 p=.026**	*Z=0.871 p=.192*	*Z=3.4408 p=<.001**
NBR 6348HS		*Z=0.792 p=.767*	*Z=2.067 p=.018**	*Z=0.454 p=.325*	*Z=0.256 p=.665*	*Z=3.548 p=<.001**
NBR 6329			*Z=1.774 p=.038**	*Z=0.020 p=.492*	*Z=0.845 p=.801*	*Z=3.6843 p=.001**
NBR 6311				*Z=0.971 p=.166*	*Z=2.053 p=<.020**	*Z=0.726 p=.234*
NRL					*Z=0.391 p=.348*	*Z=2.326 p=.010**
NRL (10% filler)						*Z=0.028 p=<.001**

** Indicates statistical significance (p<.05)*

Table 6.10. Number of pins dropped, and washers knocked off in the assembly test.

Glove	Parts dropped	No of participants who dropped parts	Average of all participants	Knocked off	No of participants who contributed to knocking pins off	Average of all participants
Bare	2	2	0.1	1	1	0.05
NBR 6348HS	10	6	0.48	6	6	0.29
NBR 6329	21	16	1.00	7	5	0.33
NBR 6311	29	12	1.38	15	9	0.71
NRL	25	14	1.19	6	4	0.38
NRL (10% filler)	9	7	0.43	6	3	0.48
PVC	49	20	2.33	37	19	1.76

6.4.4.1 Physical property correlation

As mentioned in Chapter 4, as industries measure glove parameters to EN standards, correlations were drawn between the measured physical properties and the dexterity scores obtained from both the combined and the assembly pegboard test. In addition to this, the sample stiffness has been calculated, as previously described (equation 4.1), and correlated to the dexterity performance. Moderate positive correlation is noted in the force at break in both the combined (r=.539) and assembly tests (r=.627), as displayed in Table 6.11. The correlation tests also indicate that the elongation properties have stronger positive correlation in the assembly tests (r=.774), but a weaker negative correlation in the combined tests ($r=.466$). None of these correlations show any significant differences ($p>.05$). On the other hand, stiffness is shown to have statistically strong correlations with both the combined ($r=-.888$; $p=.018$) and the assembly tests ($r=-.930$; $p=.007$), as shown in Figure 6.16. The stiffer PVC glove has shown to decrease the average pegboard score by 14.9 (±10.5) % with the combined test, and by 21.0 (±12.4) % in the assembly test, when compared to the high scoring, least stiff NRL (with filler). This indicates that the less stiff the glove is, the better the performance in the dexterity tests.

Table 6.11. Pearson's correlation coefficients of measured physical parameters.

	Combined		Assembly	
	r	*p*	*r*	*p*
Force at break	.539^Δ	*.270*	.627^Δ	*.184*
Tensile Strength	-.247	*.637*	.488^◊	*.326*
Elongation	-.446^◊	*.427*	.774^Δ	*.071*
Stiffness at 100% strain	-.888^¤	*.018**	-.930^¤	*.007**

*r= Pearson correlation score. p= statistical significance. ^Δ denotes weak correlations,^◊ denotes moderate correlations^¤ denotes strong correlations * denotes statistically significant differences (p<.05)*

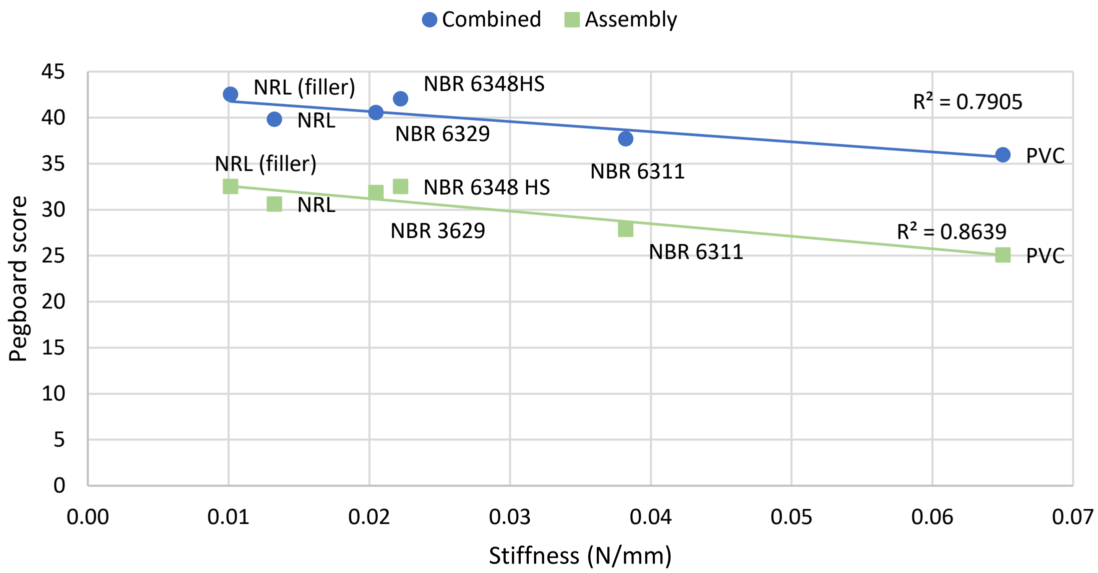


Figure 6.16. Pearson correlation graph of combined Purdue pegboard scores to the stiffness parameter of the gloves used.

6.4.5 Friction

The results of the static friction for each glove and the CoFs are shown in Figure 6.17 (a-b). In this experiment, the gloves have shown to reduce friction when compared to the no gloves condition. Friction increases across the increase in load with all materials and the no-gloves condition. Noticeably, the skin CoF reduces between the minimum (~1 N) and maximum (~5 N) target load, whereas the glove CoF increases slightly between the two extremes. ANOVA tests were conducted at each load and statistically significant differences between results are indicated (1N *F(6,14)=451.186*, *p=.001*; 2N *F(6,14)=625.368*, *p=.001*; 3N *F(6,14)=613.098*, *p=.001*; 4N *F(6,14)=593.868*, *p=.001*; 5N *F(6,14)=591.329*, *p=.001*). The results of the post-hoc Tukey's test are shown in Tables 6.12-6.16, showing that the bare hand condition has significantly higher CoF than each of the glove conditions at each given load (*p<.05*). Between gloving conditions, the NRL gloves produce the highest CoF, ranging between 1.22 (±0.12) and 1.52 (±0.08). There is little difference between CoFs across all loads with the NRL and the NRL with filler, which show no statistically significant differences at each load. However, the CoF of the NRL with filler is slightly higher on average. For example, at ~2 N, the NRL without filler averages a CoF of 1.60 (±0.02) and when filler is added the CoF is slightly increased at 1.65 (±0.03). A similar result is shown for the ~5N load, however the NRL is shown to have a slightly higher friction (μ= 1.52 ±0.02) than the NRL with filler (μ= 1.50 ±0.01). Among the different NBR grades, 6311 produces a higher friction than the 6329 and 6348HS gloves. The CoF of the 6311 is shown to be significantly different from all gloves, with the exception 6329 at the 4 N load (*Q=11.859, p=.082*). Both the 6348HS and 6329 grade gloves produce similar friction coefficients at each load, with no significant differences. The lowest friction is produced in the PVC gloves, showing friction coefficients between 0.51 (±0.05) at the minimum applied force, and 0.69 (±0.01) at the maximum applied force. The results of all CoFs produced in the PVC condition show statistically significant differences from all other gloves at each load (*p<.05*).

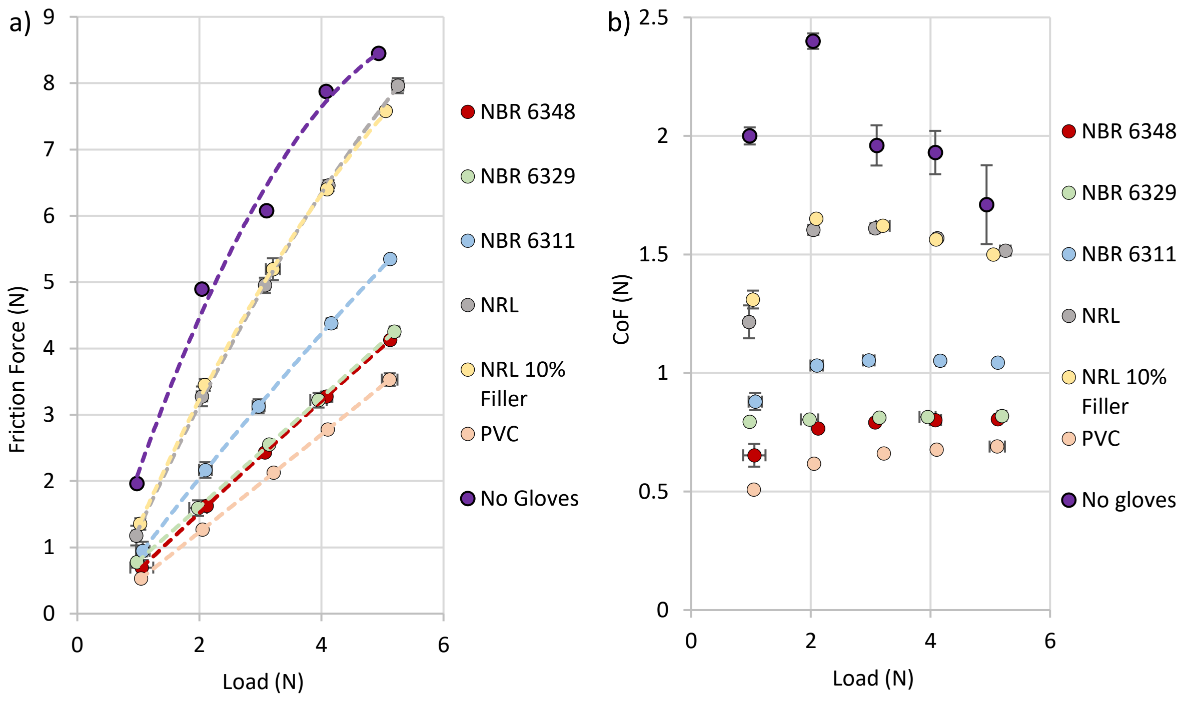


Figure 6.17 (a-b). Friction and CoFs of different gloving conditions and no-glove condition. Error bars denote standard error.

Table 6.12. Results of Tukey post-hoc test for all glove conditions at 1 N target load. ANOVA: $F(6,14)=451.186$, *p=.001*.

Glove	NBR 6348HS	NBR 6329	NBR 6311	NRL	NRL (10% filler)	PVC
Bare	*Q=56.670 p=<.001**	*Q=50.924 p=<.001**	*Q=47.439 p=<.001**	*Q=33.688 p=<.001**	*Q=29.849 p=.001**	*Q=62.592 p=<.001**
NBR 6348HS		*Q=5.149 p=.216*	*Q=9.231 p=.001**	*Q=22.927 p=.001**	*Q=26.821 p=<.001**	*Q=5.922 p=.009**
NBR 6329			*Q=3.485 p=.182*	*Q=17.236 p=<.001**	*Q=21.075 p=.001**	*Q=11.668 p=.001**
NBR 6311				*Q=13.751 p=.001**	*Q=17.590 p=.001**	*Q=15.153 p=.001**
NRL					*Q=3.839 p=.122*	*Q=28.904 p=<.001**
NRL (10% filler)						*Q=32.743 p=<.001**

** denotes statistical significance (p<.05)*

Table 6.13. Results of Tukey post-hoc test for all glove conditions at 2 N target load. ANOVA: $F(6,14)=625.368$, *p=.001*.

Glove	NBR 6348HS	NBR 6329	NBR 6311	NRL	NRL (10% filler)	PVC
Bare	*Q=134.870 p=<.001**	*Q=132.12 p=<.001**	*Q=115.83 p=<.001**	*Q=74.733 p=<.001**	*Q=71.360 p=.001**	*Q=145.54 p=<.001**
NBR 6348HS		*Q=2.571 p=.084*	*Q=19.042 p=<.001**	*Q=60.140 p=.001**	*Q=63.513 p=.001**	*Q=10.669 p=.007**
NBR 6329			*Q=16.291 p=.001**	*Q=57.389 p=.001**	*Q=60.762 p=<.001**	*Q=13.420 p=<.001**
NBR 6311				*Q=51.098 p=.001**	*Q=44.471 p=.001**	*Q=29.711 p=.001**
NRL					*Q=3.373 p=.273*	*Q=70.810 p=.001**
NRL (10% filler)						*Q=74.183 p=.001**

** denotes statistical significance (p<.05)*

Table 6.14. Results of Tukey post-hoc test for all glove conditions at 3 N target load. ANOVA: F(6,14)=613.098, *p=.001*.

Glove	NBR 6348HS	NBR 6329	NBR 6311	NRL	NRL (10% filler)	PVC
Bare	*Q=59.106 p=<.001**	*Q=58.201 p=<.001**	*Q=41.064 p=<.001**	*Q=21.400 p=<.001**	*Q=20.940 p=.001**	*Q=65.150 p=<.001**
NBR 6348HS		*Q=0.905 p=.901*	*Q=12.042 p=.001**	*Q=37.707 p=.001**	*Q=38.167 p=<.001**	*Q=6.044 p=.011**
NBR 6329			*Q=11.137 p=<.001**	*Q=36.802 p=.001**	*Q=37.262 p=.001**	*Q=6.942 p=.003**
NBR 6311				*Q=25.664 p=<.001**	*Q=26.125 p=<.001**	*Q=18.086 p=.001**
NRL					*Q=0.460 p=.890*	*Q=43.751 p=<.001**
NRL (10% filler)						*Q=44.211 p=.001**

** denotes statistical significance (p<.05)*

Table 6.15. Results of Tukey post-hoc test for all glove conditions at 4 N target load. ANOVA: F(6,14)=593.868, *p=.001*.

Glove	NBR 6348HS	NBR 6329	NBR 6311	NRL	NRL (10% filler)	PVC
Bare	*Q=57.178 p=<.001**	*Q=56.512 p=<.001**	*Q=44.653 p=<.001**	*Q=18.821 p=<.001**	*Q=19.087 p=.001**	*Q=63.391 p=<.001**
NBR 6348HS		*Q=0.666 p=.901*	*Q=12.525 p=.093*	*Q=38.358 p=<.001**	*Q=38.091 p=.001**	*Q=6.213 p=.008*
NBR 6329			*Q=11.859 p=.182*	*Q=37.691 p=.001**	*Q=37.425 p=<.001**	*Q=6.878 p=.003*
NBR 6311				*Q=25.833 p=.021**	*Q=25.566 p=.001**	*Q=18.737 p=<.001**
NRL					*Q=0.267 p=.899*	*Q=44.570 p=<.001**
NRL (10% filler)						*Q=44.304 p=.001**

** denotes statistical significance (p<.05)*

Table 6.16. Results of Tukey post-hoc test for all glove conditions at 5 N target load. ANOVA: $F(6,14)=591.329$, $p=.001$.

Glove	NBR 6348HS	NBR 6329	NBR 6311	NRL	NRL (10% filler)	PVC
Bare	*Q=51.918 p=<.001**	*Q=51.073 p=<.001**	*Q=37.515 p=<.001**	*Q=8.99 p=<.001**	*Q=9.951 p=<.001**	*Q=58.877 p=<.001**
NBR 6348HS		*Q=0.845 p=.582*	*Q=14.403 p=<.001**	*Q=42.926 p=.001**	*Q=41.961 p=<.001**	*Q=6.960 p=.003**
NBR 6329			*Q=13.556 p=.001**	*Q=42.081 p=.001**	*Q=41.117 p=<.001**	*Q=7.805 p=.001**
NBR 6311				*Q=28.524 p=<.001**	*Q=27.558 p=.001**	*Q=21.362 p=.001**
NRL					*Q=0.966 p=.900*	*Q=49.886 p=.001**
NRL (10% filler)						*Q=48.923 p=<.001**

** denotes statistical significance (p<.05)*

6.4.5.1 Correlation to performance and glove stiffness

Performance

Weak correlations are noted between the dexterity performance scores obtained and the CoF at each load (Table 6.17). The most pertinent load is likely to be at the lower 1 N grasp force (218), which shows no correlation with the combined test ($r=.087$), but a slightly stronger correlation is observed in the assembly test ($r=.397$). This implies that dexterity performance is not greatly influenced by the glove friction.

Table 6.17. Correlation of friction at each load to the dexterity performance scores.

		Force (N)				
		1	2	3	4	5
Combined	*r*	.087	.447	.425	.413	.409
	p	*.871*	*.374*	*.401*	*.416*	*.421*
Assembly	*r*	.397	.423	.402	.392	.391
	p	*.436*	*.403*	*.429*	*.442*	*.443*

r= Pearson correlation score. p= statistical significance.

Stiffness

The glove stiffness has been compared with the friction coefficients obtained, which are shown in Table 6.18. Moderate correlations are shown between the friction and the stiffness of the different gloves. However, none of these results show statistical significance. The greatest correlation is shown at the 1 N force ($r=-.735$; $p=.096$), which is shown in Figure 6.18. The correlations imply that the stiffness affects the frictional properties of the gloves, whereby the stiffer the glove, the lower the friction coefficient.

Table 6.18. Correlation of friction to glove stiffness.

	Force (N)				
	1	2	3	4	5
r	-.735◊	-.679◊	-.665◊	-.659◊	-.663◊
p	*.096*	*.138*	*.150*	*.155*	*.151*

r= Pearson correlation score. p= statistical significance. ◊ *denotes moderate correlations*

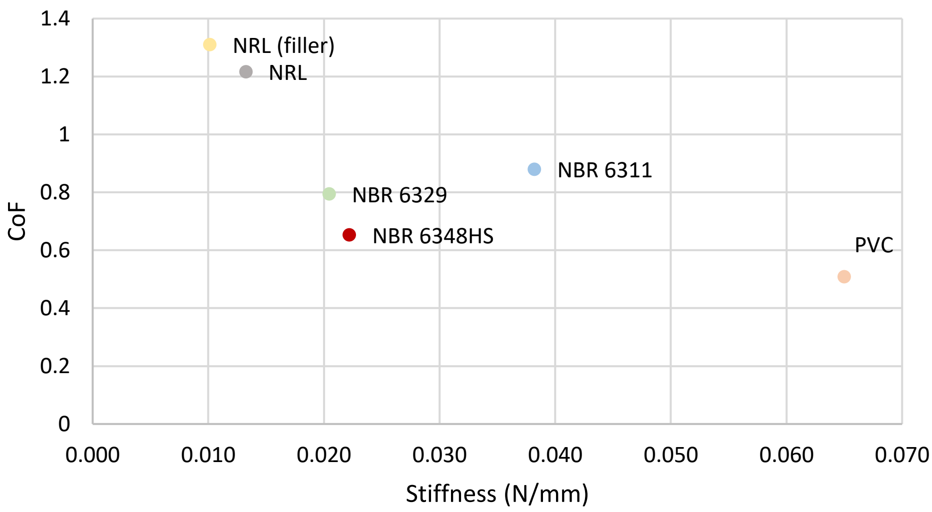


Figure 6.18. Correlation of stiffness to the friction coefficient at 1 N (*r*=-.735).

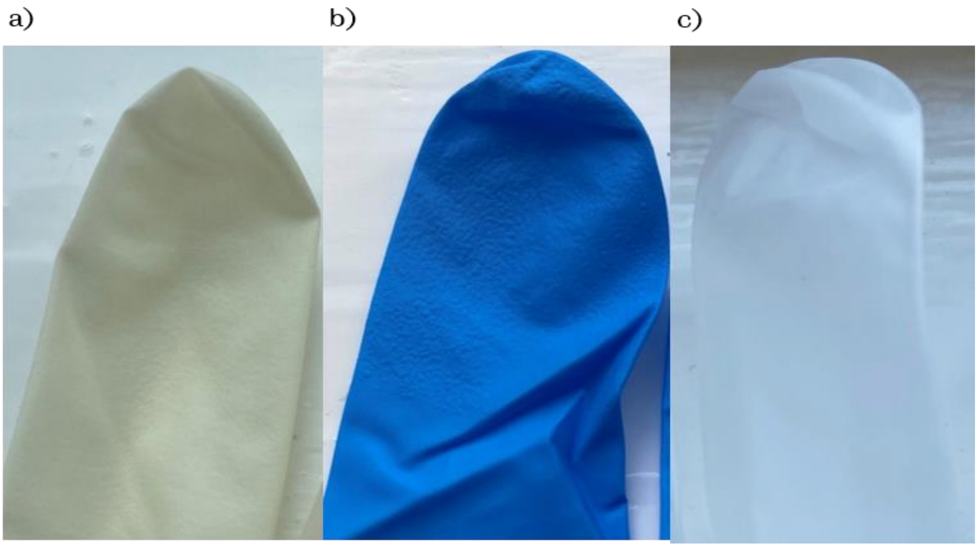
6.5 Discussion

6.5.1 Performance and friction

The results show, on the whole, that dexterity is adversely affected when gloves are donned compared to the bare hand. This was also shown with previous studies (63, 70, 75, 96) which compare dexterity with a pegboard using NBR or NRL gloves. However, the nature of the glove materials used in this study is much more understood than in previous studies, as the constituents are known, and the physical parameters have been studied.

Carré *et al.* (90) studied the friction of NRL surgical gloves. The authors found that friction was reduced when gloves were worn, compared to that of bare skin. Similar findings were produced in this study. Furthermore, this study has highlighted that gloves of the same bulk material have different frictional properties, and in turn, different dexterity performance scores. NBR 6311 shows to have the highest friction of the three NBR gloves, and the lowest performance scores. Although NBR 6348HS and 6329 show similar frictional properties, the performance was overall better with the

6348 gloves. In addition to adhesion of the gloves to the metal, contact areas could be the reason for the differences in frictional performance (189). This is a limitation of studies involving gloves from different manufacturing plants, as different formers and pattern imprints may be used. The differences are visible in Figure 6.19 which shows the NRL (Figure 6.19a), NBR (Figure 6.19b), and PVC (Figure 6.19c) finger patterns. The PVC shows to have no visible pattern on. Thus, in comparison to the other gloves used, the PVC glove is 'smooth'. The NRL shows to have a rougher texture all over the glove surface, whereas the NBR shows to have a smooth area which is then textured at the finger pad only. This grooved surface may be the cause for the reduction in friction between the textured gloves. In the skin, the rough, grooved finger pad will cause a reduced contact area, however moisture in the skin will cause capillary adhesion, whereby the finger will have more interaction with the metal due to the asperity contact and surface attraction, which has been discussed in Chapter 4. At higher loads, the finger ridges are deformable, which will cause an increased contact area through rough-rough asperity contact, to help gain friction (219). When gloves are donned, as no moisture is present, the capillary adhesion between the glove and the metal is reduced severely, leading to a decrease in friction. As the NBR surface appears more textured, there will be less contact of the two surfaces.



Figures 6.20a-c. Figure a shows the NRL glove fingertip, b shows NBR 6311 and c shows the PVC.

Positive correlations were noted between the friction of the gloves and the stiffness, a correlation also noted in Chapters 4 and 5. The NRL gloves have a lower stiffness, indicating that they are easier to deform. Thus, when the greater forces are applied, the more the NRL will deform and increase the contact surface area, increasing the friction. As the NBR is more rigid and stiff, there will be less deformation and the rough applied pattern will keep the surfaces separated, resulting in lower contact areas and lower asperity contact. Therefore, in the NBR and NRL gloves, the lower stiffness allows for deformation of the local asperities, likely inducing local welding and making the static friction harder to overcome. On the other hand, in the stiffer PVC, the asperities will sit atop the smoother surface and little deformation will occur. Thus, friction is lower in the smoother PVC glove, as shown in Figure 6.20. This is similar to the friction between the skin and the gloves discussed in Chapters 4 and 5. However this time, the deformability of the glove is increasing friction by increasing the contact of asperity junctions, whilst the stronger gloves do not deform, reducing friction. In Chapter 5 it was shown that the donning gloves had different frictional behaviours based on the stiffness. The higher stiffness exhibited more stick-slip as the finger was run down the glove, whereas the less stiff gloves exhibited more movement as the glove stuck to the fingers more. However, with the gloves used in this study, different thicknesses are apparent throughout the gloves, which may have an effect on the friction due to the differences in bulk material properties.

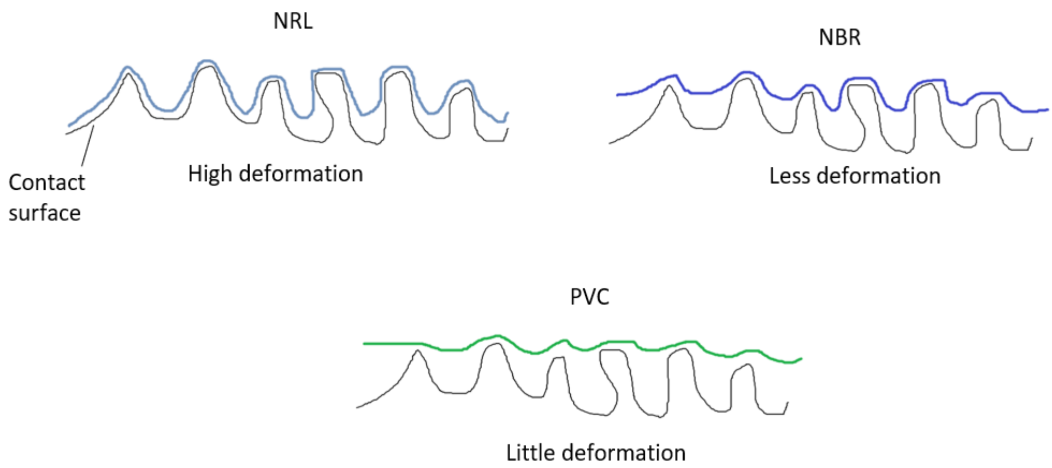


Figure 6.20. Schematic of the glove-metal asperity contact.

Due to the translucent nature of both the PVC and NRL, surface roughness details were unobtainable as the method of surface roughness used deploys optical microscopy. However the physical glove properties appear to be a greater factor than the surface roughness. The PVC is also shown to have the poorest performance, with more pins/assembly parts being dropped on average than any other condition. This leads to the inference that the frictional properties have led to the differences in performance.

Capillary adhesion

The moisture in the bare skin is a reason for the differences in performance in the bare hand condition. Although this is not shown in the results due to the normalisation, there was some variation in the results. The reason for these differences is mostly down to the dexterity of each individual conducting the test. In conjunction with this, however, the friction when grabbing the pins is also an important factor to consider. It is important to note all gloving conditions either decreased performance or matched the score in all participants. No one person performed better in any gloved condition than their no gloves score. An increase in surface contact area is possible due to the introduction of moisture in the skin. This can cause the two surfaces to pull together, and friction will greatly increase. However, this is applicable to hard but rough surfaces, and not necessarily the case when one of the materials is soft (189, 220). A study by Persson (105), shows that when water is decreased between elastically deformable solids, the area of contact greatly increases. This effect has been demonstrated and discussed in Chapter 4 (see Section 4.5.1). However, this friction was dependent on two deformable solid materials, whereas this friction is between the skin and metal surface. This effect of the increase in friction is said to be dependent on the Young's modulus of the materials in contact (105, 121). In the skin, the top layer (stratum corneum) will have a varied Young's modulus between participants, due to the differences in components in the skin, and the moisture content (221). Where the bare hand test is being conducted, the Young's modulus of the stratum corneum is the most salient factor in whether capillary adhesion will occur to increase friction. No water or increased moisture was used in this study, therefore the differences in capillary adhesion between the skin and the metal is likely to not be as great an effect as discussed in previous chapters. However, it could be argued that this adhesion is vital for precision control when placing the pins. When gloves were donned, which contain no moisture, the friction of all gloves decreased in comparison to the bare hand, as demonstrated with the sole participant in the friction study. This is possibly because the adhesion between moisture, in the stratum corneum, and the metal is blocked by the glove. It may be possible that this capillary adhesion could allow for a better grip and sensibility regarding the task, allowing for greater precision when placing the pins/parts.

The role of capillary adhesion in grip has been studied previously, revealing it may only have a little effect, if any, on the role of friction. Pailler-mattéi and Zahouani (222) studied the 'pull off' force of a steel probe on the forearm skin and found the capillary adhesion forces to be around 5 mN. The small values, which are a small percentage of the force applied in normal tactile exploration, are also found throughout other studies (104, 218). Therefore, there is little evidence suggesting that the capillary adhesion of the skin is a significant factor in friction in this study. However, it should not be ruled out as a factor entirely. It is likely that the frictional differences observed in this study are combined a result of the deformability of the gloves as previously discussed, leading to an increase or decrease of asperity contact, which may be shaped by capillary adhesion in the skin.

6.5.2 Physical properties

It could be argued in these tests that the measurements conducted when gloves are worn depend on the glove friction, rather than dexterity. As, for example, the lower friction in the PVC gloves lead to more pins being dropped in the performance tests. However, this study shows this is not likely to be the case and is more of a combination of dexterity and friction. As the loads used by the participants in the dexterity test will vary, more force could be applied to hold and place the pins/parts. In order to assess the correlation between the friction of the gloves and the performance accurately, there needs to be a constant force applied with each glove in order to fairly assess these parameters. However, the fact that there are correlations between the stiffness of the gloves, with both the friction and the performance implies that friction is important. For example, the NRL gloves show differences in performance, but similar frictional behaviour. When filler is added to NRL, the gloves become less stiff than when no filler is added. However, there are slightly different performance scores between the two gloves. Additionally, there are positive correlations noted between both the elongation of the gloves and the performance. In the combined test, this correlation is negative. The correlation between elongation and the performance in the assembly is stronger, which shows better correlation between the score and the elongation. This correlation was also noted between the donning time and elongation in Chapter 4, giving further evidence that elongation may provide an indication to the performance of examination gloves.

6.5.3 Effects of gloves on dexterity

There is little discussion in the literature on how gloves affect dexterity enough to conclude that a decrease in performance is detrimental. Proud, Miller, Bilney, *et al.* (223) studied the use of the Purdue pegboard with patients diagnosed with Parkinson's disease. The study compared the results to those who did not have Parkinson's, and found on average, those with the diagnosis placed 12.4 fewer pins. In this study, the greatest difference to the bare hand was found to be 10 fewer pins placed on average when the PVC glove was worn, indicating a greatly reduced performance. Morris (224) and Korniewicz, Garzon, Seltzer, *et al.* (225) suggest that dexterity is affected by gloves through inducing hand fatigue over time. However, little work has been conducted into how this causes fatigue, and results in a loss of dexterity. From the review of the work looking at dexterity, it is clear that many of these types of tests are short and succinct. For example, this test took the participants each 2.5 minutes to do all of the tests, with breaks in between whilst the board was cleared, and participants rested. This is the case for many of the tests conducted in the literature, and far fewer test conditions are normally used (6, 9, 12). Therefore, it is more likely that the reason for dexterity loss is through the gloves restricting lateral movement of the joints between the fingers, as well as movement of the thumb both horizontally and laterally, rather than solely a time-dependent issue.

Hubner, Goerdt, Mannerow, *et al.* (226) also show that gloves tend to have a higher failure rate (more perforation) between the index finger and the thumb, indicating more stress is put in this area. It is likely that this wear is present as the glove is stretched and relaxed more due to the natural movement involved in gripping. In this study, participants grabbed parts predominantly with a pinch-grip, holding pins between the thumb, index, and middle finger as in Figure 6.21. Thus, if the glove is restricting the natural movement of this thumb-finger area, the participant may struggle to conduct the task when trying to grab the pins.

Figure 6.21. Pinch grip exhibited with pin grabbing and placement amongst the participants.

It is thought that if the gloves are stiffer, this would be harder to move more naturally, due to the resistance of stretching from the glove. The results of this study do provide some evidence for this. The PVC gloves scored the lowest on average in both of the tests. This glove was shown to be the stiffest of all of the gloves used, whereas the NRL which contained adulterants was the least stiff and performed better overall. In addition, the stiffer nitrile glove (NBR 6311), was shown to perform the worst out of all the NBR gloves used. In conjunction, correlations were found between the glove stiffness and the performance score with both of the tests.

To highlight the effects these different gloves may have on the restriction of movement a small test was produced to assess how hand span may be decreased with donned gloves. Figure 6.22 shows the hand is placed as wide as possible on a series of grids (1cm × 1cm). Each of the gloves was then donned and placed onto the grid to assess any visual reduction in hand span. However, this is a rudimentary test which would require a greater assessment with a larger number of gloves, and participants with different hand sizes, in order to form a solid conclusion on the hypothesised effects.

Nevertheless, it can be seen that when the stiffer PVC glove is donned, the glove restricts adduction of the thumb. Thus, when doing tasks quickly, the restriction may have an effect on the psychomotor ability due to the small differences in freedom of movement. In addition to this, it can be seen there is excess material between the fingers with the PVC, but not with the NRL, highlighting issues with the sizing of gloves and further indicating a restriction of movement of the fingers.

Figure 6.22. Left: hand spanned without gloves. Centre: hand spanned with NRL. Right: hand and spanned with PVC gloves.

The knocking of the washers in the assembly test strengthens this reasoning. A total of two washers were accidentally knocked off the completed assemblies in the bare hand condition. However, when gloves were donned, more washers were knocked off. The PVC glove shows a greater number of washers being knocked off. The knocking off of the parts could be due to a combination of the compression of the hands, the gloves restricting movement, and the overall feel of the gloves. This indicates that once the gloves are donned, the movements are less co-ordinated, showing that the gloves do decrease dexterity. A greater bank of gloves should be analysed, with known chemical compositions, as in this study, in order to fully understand the effects these gloves have on dexterity. It was previously postulated by Mylon *et al.* (8) that the combined portion of the Purdue pegboard test is redundant for use in glove assessments. However, this test is becoming a more widely used and standardised test for motor skill assessments. Using the board between studies, where the exact components and physical characteristics of the gloves are known could prove useful for assessments by manufacturers, as this study shows measurable differences.

Comparison of common gloves

A common theme noted in the review of literature in Chapter 2 was the frequency of studies comparing NRL and NBR gloves. This leads to a underlying theme in the literature of comparing the two gloves, where similar or slightly differing results are shown (6, 9, 12). Although this study is similar to the other studies in respect to this comparison, the addition of the chemical knowledge and differences between the bulk materials is advantageous for better understanding the effects of gloves on performance. As discussed earlier, comparing studies where chemical/material information is not ascertainable does not allow for a fair comparison. It would seem that the comparison of NRL and NBR gloves has reached its course without the fundamental understanding of why or how dexterity is affected. Very little differences exist between the two gloves in terms of performance in this area. However the NRL does provide slightly better dexterity than the different grades of NBR. Although the NBR does show remarkably similar results. Future work in this area should focus on much longer tasks, looking at the induction of hand fatigue proposed by Morris (224) and Korniewicz *et al.* (225) whilst giving great consideration to the physical and frictional properties. Whilst it could be argued that examination gloves are used for a short amount of time, therefore studies looking at prolonged use would be more pertinent to surgical gloves, examination gloves are worn across many fields. In clinical settings, a frequent glove change is encouraged to avoid cross contamination. However, in roles such as mechanics, forensics, cleaning, laboratory work etc., gloves will be worn much longer without the need for frequent changes.

6.5.4 Glove size and fit

There is some mixed messaging regarding how the fit of gloves affects dexterity. Drabeck *et al.* (99) speculates that the thickness of NRL surgical gloves impairs the dexterity of glove users, and the dexterity is rather unaffected by the glove size. On the other hand the authors found in another study that wearing vinyl gloves did not impair manual dexterity (97). Mylon *et al.* (70) also showed that wearing gloves larger than the perceived best fit diminished dexterity when using the Purdue pegboard. Although differences in glove size performance was not assessed in this study, it is clear that glove sizing is an inherent issue.

It was discussed in Chapter 4 how the fit of gloves may not account for the general population, which has also been highlighted in this study. Of the 21 participants only four had gloves that fit into the HSE guide chart. In Chapters 4 and 5, only four of the 20 participants used in both of the donning studies had gloves that fit the participants recommended size. Ooka and Morimoto (227) assessed the perception of fit on 325 female dental students. They found the participants had 'optimum' perceived best-fit when the gloves had slightly shorter fingers than the participant. This study shows similar findings, with the gloves being shorter than the fingers, which shows conformity to the fingers. The less stiff the glove, the better the gloved looked to fit. However, Ooka and Morimoto's (227) findings are only applicable to the less stiff gloves. As discussed around Figures 6.10-6.13, there are areas where the gloves are visibly shorter than the fingers in the PVC gloves.

However, the gloves are all the same gross size (medium), and therefore should have very little difference between the sizing and fit. Measurement of the gloves themselves, however, do show very slight differences in the sizes of gloves. The most variation is noted at the total length, which is likely a result of the difference in the dipping process and/or how far down the glove is beaded. More emphasis should be placed on the differences in measurements at the finger length, palm span, and finger width. The palm span was shown to differ most in the NBR 6311 and the PVC gloves. Although the difference is not great between the two gloves, it would indicate that a perfect fit with the NBR 6311 glove would lead to some excess material with the PVC glove. This is likely to arise due to a possible variation in former size, rather than the manufacturing process.

Glove formers and fit

The glove formers used to manufacture gloves can be purchased by different manufacturers, and due to the difference in the glove sizes there is a suggestion that the formers differ in geometry, even in the same sizes. One company was found selling two different formers for medical examination gloves with sizes extra small, small, and medium. When compared, the formers were found to have different dimensions, as shown in Table 6.19 (228). As the total glove length is dependent on the manufacturing dipping process, the height is arguably unimportant, as long as the gloves can be dipped to similar lengths. However, there are differences highlighted between the formers. As much as a 2 cm difference is shown in the medium sized former at the height. The greatest difference noted at the palm circumference is in the extra-small gloves (6 mm difference). The wrist circumference with the greatest difference is noted in the extra-small and the medium formers (2 mm difference).

Table 6.19. Former sizes obtained from one former manufacturer (228).

	Extra-small		**Small**		**Medium**	
	Former 1	**Former 2**	**Former 1**	**Former 2**	**Former 1**	**Former 2**
Height (mm)	400	380	400	380	400	380
Palm circumference (mm)	170	164	177	178	202	202
Wrist circumference (mm)	151	149	166	167	180	182

A question arises as to why these medical glove formers are different geometries for the same sized gloves. There is no literature guidance surrounding the shrinkage of films once removed from the former, such as if particular gloves shrink to a particular size when removed. As the chlorination process, and other treatment processes, harden the surface of the glove, it is highly unlikely that there is any significant film shrinkage once the glove is stripped from the former (51). As the gloves being made are sized in increments of extra-small, small, medium, large, and extra-large, it is likely that that one former size should be used to yield the respective glove size, regardless of the bulk material being used. This size variation between formers, that is prevalent throughout the industry, causes fitting problems, whereby one user may be a between sizes or have to use different sizes for different brands. In an emergency, this causes complications with the ability to don the gloves (as highlighted in Chapters 4 and 5), and with the user performance, such as tactility and dexterity as seen in this chapter and with previous studies (70, 72, 99). The sizing of gloves was highlighted as a concern in Chapter 3, with 62% of the participants indicating that the size of gloves they routinely wear do not properly fit. By virtue of the formers mimicking the hands, the sizes must be based on the anthropomorphic sizes of the hands of a general population. However, no information can be found on the sizing regarding former manufacturing, and it is difficult to ascertain how these sizes have been developed and established worldwide. Given some of the variations in size and how these relate to the populations using the work in both this chapter, and in Chapters 4 and 5, it is clear to see why participants who responded to the questionnaire in Chapter 3 stated that they believe they are 'between' the glove sizes available. This was more prevalent in the NBR gloves. Although, more users stated they wore NBR, the perception of NBR being 'between sizes' could be down to the stiffness, the gloves not conforming to the hand, and having a 'looser' feel as indicated by Ooka and Morimoto (227). As with much of the PPE, it is highly likely that the formers existing today are based on the producing gloves fit for a male population. This is a timely issue, with the Royal College of Nursing stating the problem of a one-size fits all sizing system is problematic for female nursing staff (229). This problem has also been highlighted as more PPE is required, where it may have not been use previously, over safety concerns regarding the covid-19 pandemic (177).

Anthropomorphic data, over time, has shown that there are clear and distinct differences between hand sizes between men and women (230). Furthermore, hand sizes have been shown to variate throughout different races (231). It is clear that the gloves manufactured today are not the 'one size fits all' that they perhaps were when glove manufacturing became more prevalent. Although, it is appreciated how difficult it would be, from a manufacturing point of view, to differentiate and create different sizes for different populations. On the other hand, a more specific sizing does exist for the use of surgical gloves (99). Data is available that strongly indicates that glove sizing requires a lot more research and changes should be made to ensure the safety of users, and to not adversely affect performance. If glove sizes cannot be accurately ascertained by glove users, there is a potential for diminished performance with regards to dexterous tasks (70, 99).

6.6 Conclusions

Figure 6.23 summarises the findings in this chapter by showing the effects of stiffness on the measured performances and ranks the gloves by their effects on dexterity.

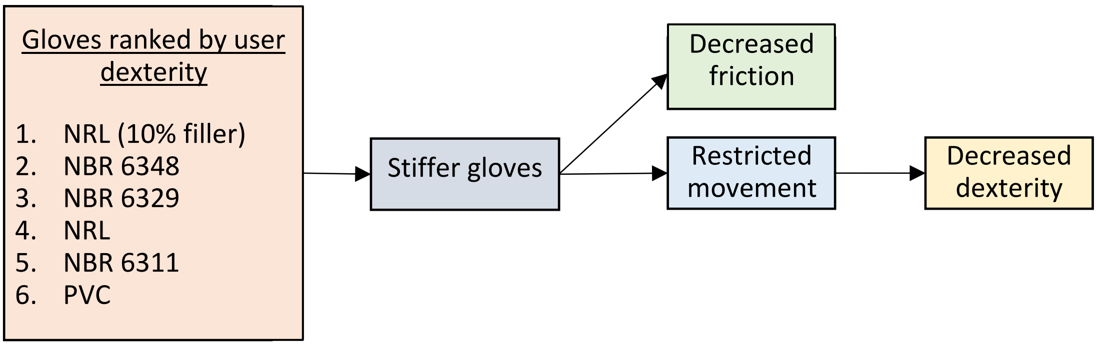


Figure 6.23. Summary of chapter findings, showing the effects of the different materials on dexterity. NRL with filler offers better dexterity, due to less restricted movement.

The findings of this chapter are:

- Dexterity of the participants was affected by the examination gloves used in this study, and the differences in properties between gloves play an important role in both the friction and dexterity of the gloves. The work conducted also highlights that gloves between studies cannot be accurately compared, as previous studies looking at dexterity with different gloves will have fundamental differences in their physical properties. In this study different grades of NBR have different properties, leading to a difference in overall dexterity amongst the glove users.
- The fundamental causes for differences that are apparent in studies of this nature are not well understood. This study finds strong correlations between the glove stiffness and the performance, which strongly indicates that a stiffer glove (such as the PVC) adversely affects performance. This is hypothesised to restrict movement around the fingers, which decreases dexterity. The stiffer gloves in this study were shown to reduce the dexterity of the participants, whereas the less stiff gloves showed to increase the participants dexterity. Further work assessing why, and how, medical gloves affect dexterity is pertinent to the understanding of how to overcome issues whereby gloves decreased dexterity. Understanding the parameters which may affect the gloves will allow the manufacturers to understand and predict how newer glove materials may affect dexterity.
- Gloves decrease the frictional properties when compared to skin. The frictional properties are found to be much lower for the stiffer gloves, due to behaviour of asperity contact.

However, little correlation was noted between performance and the friction coefficients of each glove.

- The sizing of gloves needs to be reviewed in accordance with the general population. Although the gloves in this study were chosen as participants 'best-fit' there were clear discrepancies in the fit between both participants and the gloves. Issues were also found in previous chapters regarding the fit of gloves which further highlights this issue.

Chapter Seven: Effects of contamination on glove friction

Having determined the requirement for the knowledge about the physical and chemical properties of the materials, it is clear gloves need testing in the conditions they will be used in (6, 172, 232). New industry standard testing can be difficult to implement. However, adapting existing tests to make them more replicable of the conditions glove are used in, is easier to execute. Much of the work carried out on friction has been previously discussed in Chapter 6. However, in the literature review conducted in Chapter 2, it was shown that the reason gloves are donned is neglected from these tests (6). That is, to protect the hands from contamination. Therefore, frictional properties may be affected by this contamination, which in turn, could have an effect on performance. Only two papers were found incorporating contaminants; water (114) and blood (116). This chapter of the thesis focuses on that contamination, exploring how gloves may be affected in terms of friction when exposed to a variety of substances. The frictional implications will then be discussed in terms of how they affect dexterity and sensitivity in a later chapter (Chapter 8).

7.1 Introduction

Potentially, gloves are exposed to contaminants every time they are donned, hence the reason for using them. Many of these contaminants have been discussed in Chapter 3, where it was discovered that bodily fluids make up the majority of contaminant sources. However, the main respondents of the questionnaire were from medical and clinical fields, thus the answers regarding bodily fluids are to be expected. Blood was shown to be the most common contaminant for medical gloves. However that has not been used in this chapter. This was due to reasons regarding quantity and stability over the course of the tests. Nevertheless, blood was used in other tests and is discussed later in Chapter 9.

Other than blood, the most common fluids in contact were reportedly watery solutions such as urine, sweat, water and liquid drugs. Medical disinfectants were also indicated to contaminate gloves frequently. Combined, mucus and saliva make up the second (next to blood) most common contact contaminant. A major protein constituent of these two fluids is mucin. Mucin is a central component of mucus, found in saliva, nasal mucus, and the linings of the respiratory, urinogenital, and gastrointestinal tracts (233). Composed of long peptide chains, mucins are of a characteristically high molecular mass owing to the abundance of hydrophilic carbohydrate side chains that span off the central protein (234). Due to this size, and hydrophilicity of the carbohydrates, charge repulsion enables the mucin protein to entangle and form muco-adhesive gels. When the water evaporates from the mucin gel, a thin muco-adhesive film is left behind, which can act as a tribo-film (235, 236).

Mucin was chosen due to the abundance in the body, making it a likely source of contamination for medical gloves (233).

7.2 Aim and scope

Analysing the friction present between tools and glove surfaces is key for the assessment of medical gloves. Examination gloves need to retain a certain amount of friction for the user to be able to precisely hold equipment, but not have too much friction as to make it difficult to manipulate and hinder their dexterity. In this chapter, the frictional properties of NRL and NBR examination gloves will be investigated. This includes assessing how the frictional properties change in response to contamination. The questionnaire results in Chapter 3 revealed that, other than blood, common contaminants are solvents, proteins, watery liquids, and powders. Thus, the contaminants used are centred around substances with these properties to assess how they affect the frictional properties of gloves with different tools used in clinical practice.

7.3 Materials and Methodology

7.3.1 Glove Material Selection and characterisation

Glove selection

The gloves used in this study were NRL gloves branded ‘Safe Touch’, purchased commercially, and carboxylated NBR gloves, which were obtained from Synthomer. Both sets of gloves were powder free and chlorinated. Other than the core material (acrylonitrile butadiene and natural latex), the chemistry of the glove films was not able to be determined, as detailed information regarding manufacturing was not available. Thickness of the gloves was measured at the palm and fingertips using a micrometer (Mitutoyo, quickmini ±0.01 mm), and the gloves were found to be of a similar thickness (NBR= 0.106 (±0.006) mm; NRL= 0.114 (±0.007) mm).

Surface roughness

Surface roughness was measured using the Alicona microscope (InfiniteFocusSL), as in Chapter 5. Two samples of each glove were obtained from the fingers (4.0 × 4.0 cm) and two scans (1.5 × 1.5 cm) were made of each surface, with a 5x objective lens with magnification between -5.47 – 17.11x, a lateral resolution of 3.71 µm, and a vertical resolution of 900 nm. Problems occurred with the scanning of the NRL glove due to the colour and translucency of the material, a problem which is noted in Chapters 4 and 6 with the NRL and vinyl gloves. The instrument could not scan small sections of the NRL gloves, leading to small holes in the images produced; thus, a full surface area measurement of scanned samples was not obtainable. Roughness was measured using an averaged surface roughness (Sa) of a 0.5 × 0.5 cm portion of each scan.

Atomic Force Microscopy

To assess the topography of the gloves in greater detail, atomic force microscopy (AFM) was used. One 5 × 5 mm section was cut off of three finger sections of each glove and mounted onto the AFM plate (6 samples in total). The fingers of the gloves were used for this study to assess the surface topography, as this is where the friction is most pertinent. The gloves were cleaned by the application of nitrogen gas being blown onto the surface. This removed loose contaminants that may be present on the surface of the material. AFM measurements were performed using a Bruker AFM (800 Multimode). Scans were completed using the dual pass method, whereby the scanning cantilever probe passes over the surface, taking topographical information and allowing phase images to be taken. Tapping mode was used to obtain height, phase, and amplitude measurements at ambient temperature with a dual-scanning rate of 4 and 12 Hz. In tapping mode, the cantilever oscillates up and down near the sample surface via a piezo element. The tip of the cantilever will interact with the surface of the glove film via electrostatic forces, Van der Waals bonds and dipole-dipole interaction. This causes the cantilever to change in oscillation frequency the closer the tip is drawn to the sample (237). Thus, the image produced is provided by the force of the interactions with the sample surface. Three different 2 × 2 µm areas of each glove sample were analysed. The inside of both of the gloves were also analysed for any similarities to the outer. As the gloves are affixed with a low-tack adhesive to the AFM instrument, the inner and outer surfaces are from different locations of the glove, and not the same section flipped over, as this may have incurred some contamination. Each area analysed was further zoomed in and analysed at 100 nm for further topographical information. Sample data and roughness measurements were processed using Gwyddion imaging software.

7.3.2 Contaminant selection and characterisation

Six contaminants were selected for this study, based on responses regarding common contaminants in Chapter 3. Whilst most of the contaminants suggested originate from the body, there are some which were shown to be from different origins (e.g. solvents, cleaning, oils). The contaminants selected here were chosen based on their likeness to bodily fluids, availability, ease of storage and safety of disposal. In addition to this, contaminants were selected based on their differences in properties, to allow assessment of how glove friction may be affected by the differences in behaviour and interaction. The fluids selected are based across two major professions: forensic and clinical. However some of these contaminants can be applied to multiple professions where gloves are used. A mixture of the individual contaminants was also included. This was to mimic conditions encountered when in gloves are in use, whereby contaminants may mix together, and to understand how mixtures would affect the tribology of gloves (e.g. different affinity of components for the gloves). The contaminants are shown in Table 7.1.

Table 7.1. Contaminants selected for friction assessment.

Contaminant	Constituent	Appearance	Selection rational
Alcohol	Ethanol ≥99.8% absolute with 2% chlorhexidine disinfectant	Clear, watery liquid	Comes into contact with the gloves when cleaning (such as cleaning skin) and sterilising equipment (238)
Mucin	Porcine gastric mucin protein (PGM, Type II, unpurified). [10 mg/ml] solution made with DI water	Globular liquid Colloidal proteins suspended in solution	Globular protein, which is the major component of mucus, saliva and found lining organs in the body. Mucus/saliva was said to be a common-contact contaminant in Chapter 3. The solutions display a non-Newtonian behaviour and viscosity reduces in response to shear rate increase (235)
Oil	Triglyceride fat	Viscous, greasy liquid	Constituent of fats, which can be found in the body. Questionnaire showed contaminants of steroidal oil suspensions is known to contaminate gloves when discussed in Chapter 3.
Powder	Magnesium Silicate (talc) (Johnson and Johnson)	White, fine powder	Powder residues are common from tablet handling in the medical field and are frequently encountered in the forensic sector
Water	DI water	Clear liquid	Commonly many contaminants from the body are watery in nature (e.g. urine).
Mixture	5ml Ethanol, Mucin 5ml, Vegetable oil 5ml, Baby Powder 0.5g, and 25ml water	Colloidal liquid, mucin suspended. Oil and powder on liquid surface	A mixture of the individual contaminants is included to assess differences in glove behaviour.

Viscosity

To measure the viscosity (η), 10 ml of each solution was measured with an *AND* vibro-viscometer (SV-1A, ±0.01 mPa s.). Each solution was measured three times to obtain an average. Solutions were shaken for 2 minutes before filling the sample well to disperse any colloidal suspensions and induce homogeneity. Samples were measured at room temperature (23.9-24.9°C), with the exception of mucin, which was heated to physiological temperature. As this is the only fluid being used which originates from a body, it was thought a more realistic view of the effects of the protein interaction was to heat it to physiological temperature (36-37°C).

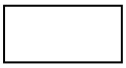
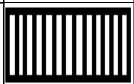
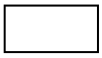
Contact angles

Contact angles were measured using the sessile drop method used in Chapter 4 and 5 (see Section 4.3.1). Samples were measured 5 times with the solutions at room temperature (24-27°C), with the exception of mucin which was heated to 37°C with a water bath. In Chapter 4, it was shown that the contact angle was not affected by the strain of the material. Thus, the gloves in this chapter were studied in an unstrained condition using the stretching device shown in Section 4.3.1 (Figure 4.5). Contact angles were determined to assess the initial interaction with the gloves and assess the wettability of the different surfaces.

7.3.3 Tool selection

The tools and patterns used in this study are shown in Table 7.2. Tools were provided by The University of Sheffield Dental School and were selected based on the difference in tool patterns on commonly used equipment. Measurements of the manufactured patterns were made using a scaled compound microscope (Kern, KEOBS-101) and a ruler. The steel strip (tool 7) is the same strip used in Chapter 6, where it was used to compare frictional performance to dexterity with pegboard pins. Where the roughness (R_a) is reported, the measurement was recorded using a surface profilometer (Mitutoyo, SJ400) over a 2.5 (±0.001) cm section with a measuring speed of 1 mm/s and a force of 0.75 mN. This was repeated three times along the surface.

Table 7.2. Tools used for analysis of frictional properties. Wavelength refers to the distance between repeating parts of the pattern.

Tool	Material	Image	Pattern shape	Pattern depth (mm)	Wave-length (mm)
1	Metal			0.02	1.0
2	Metal			0.08	2.8
3	Ceramic			Smooth R_a = 0.08 µm	
4	Metal			0.03	0.02
5	Metal			0.04	1.0
6	Plastic			0.05	3.0
Smooth	Metal			Smooth R_a = 0.11 µm	

7.3.4 Friction methodology

The methodology for the friction analysis follows the same as described out in the previous chapters but follows more closely to the friction tests designed in Chapter 6 (see Section 6.3.5). The tools were alternately fixed to the AMTI force plate and secured with tape to ensure there was no relative movement, as in Figure 7.1. Further tape was placed over the end of the tools to further secure the tools to the plate and cover the sharp edges. The angle between the finger and the surface was kept at approximately 40° in order to measure just the gloved finger pad friction. After holding the finger in place on the tools for 2-3 seconds, the finger pad was dragged along the plate to cause a sliding action (at around 0.6 mm/s). As in Chapter 6, only static friction was used for this study, as this is friction most relevant to holding tools of this nature (114, 116). Gloves were donned on the right hand of the sole participant (male, aged 28), and the tools/force plate were cleaned with acetone/water and dried before repeating with another contaminant. The gloves were also changed between contaminants to avoid cross contamination. The friction tests were carried out with both gloves in the dry condition, and with gloves exposed to each of the six contaminants (14 tests in total).

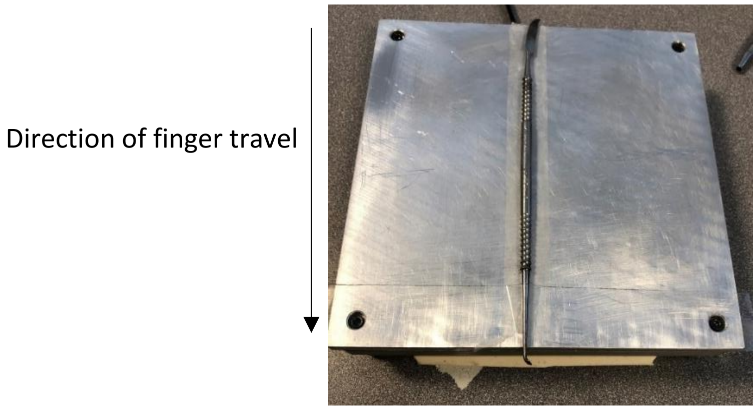


Figure 7.1. Tool 2 affixed to the AMTI force plate.

Load selection

Force selection was chosen based on the loads used in Chapter 6 for consistency. These loads were selected to replicate grip forces based on literature, as discussed in Chapter 6. The target loads selected in this study are 1, 2, 3, 4 and 5 N. A range of loads allows for the understanding of how the contaminants are changing friction with different grip force, as well as how the contaminants may change in behaviour over the load range. Tests were repeated three times at each load to obtain an average.

7.3.5 Contaminant application

Fluid contaminants were applied to the glove by dipping the gloved index finger into the fluid contaminants. The solution covered the finger up to the proximal-intermediate interphalangeal joint (around 5 cm up the finger, Figure 7.2) and was held for 10 seconds. This was to ensure coverage of the finger pad and allow interaction between the fluid and the glove film. The finger was removed, and excess fluid was shaken off of the finger before placing onto the tool.

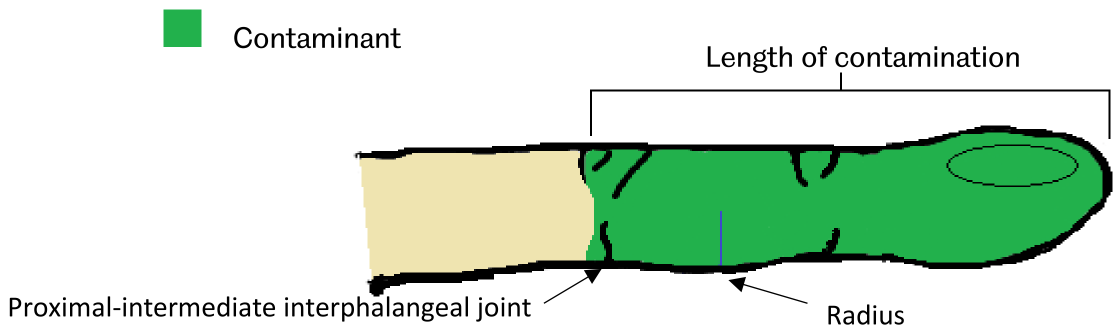


Figure 7.2. Location of contaminant on finger (shown in green) to the interphalangeal joint of the index finger.

All contaminants were tested at room temperature (22-25°C,) with the exception of mucin, which was heated to 37 (±1.5) °C via a water bath to achieve physiological temperature, as previously discussed. When the test was being conducted, the temperature of the mucin was monitored using an infrared thermometer (Raytek, RSCMTFSU ±0.5°C) from removal of the water bath to application of the tool. It was found the mucin temperature dropped 3-5°C to around (32-33°C). Initially, the mucin was going to be heated to 40-42°C in order to account for this drop in temperature. However, proteins are intricate, changing their shape and ultimately their behaviour depending on the temperature (233, 234). Changing the temperature higher could have caused some denaturation to the proteins, changing their interaction with the gloves, and lead to erroneous conclusions of their effects. Therefore, the testing was continued by initially heating the mucin to 37°C. To apply the powder, the finger pad was place in the powder, patted, and then rolled around to ensure coverage, as shown in Figure 7.3.

Figure 7.3. Powder application to the finger pad.

Contaminant mass and film thickness

To determine the amount of contaminant on each glove, the gloves were weighed using an analytical balance (Ohaus, PR124 ±0.0001 g), before and after application of contaminants. This test was conducted as a separate study to determine the differences in contaminant deposition onto the gloves and followed the same application procedure described. This was conducted three times with each contaminant to obtain an average.

The thickness of the deposited contaminants has been calculated to further highlight differences in the liquid contaminants surrounding the gloves. Whilst many instrumental methods exist to assess film formation thickness, the precision of these instruments are used to measure extremely thin films deposited onto the surfaces using controlled synthesis of materials (239, 240). Given the procedure used to deposit the contaminants, and the evaporation rate of the contaminants (such as alcohol), it was thought that instrumental analysis was not applicable. Thus, analysis has been conducted using an estimated film thickness. The estimated thickness (t) of each film was calculated using the density (ρ) and the mass (m) transfer of the contaminants to the calculated surface area (a) of the glove (239, 241). Estimated film thickness was calculated using Equation 7.1.

$$t = \frac{m}{a \times \rho}$$

Equation 7.1

Density (ρ) was calculated by pipetting (Scorex, Acura ±5 µL) 1 ml of each sample to a pre-weighed Eppendorf tube. The density was then calculated using Equation 7.2.

$$\rho = \frac{m}{V}$$

Equation 7.2

where m is mass of solution and V is volume. The area with which the finger was contaminated (A) was calculated using the formula for a flat ended cylinder (with only the area of one flat end calculated), by using Equation 7.3.

$$A = (2\pi\, r\, l) + (\pi\, r^2)$$

Equation 7.3

where r = radius and l = length, depicted in Figure 7.3. It is appreciated this method of determining film thickness has some shortcomings, as it assumes that the shape, and that the film is even and uniform along the entire surface, and the same volume of liquid is on the finger in every friction test. However, together with the calculations of how much of the contaminant is deposited onto the finger, these calculations highlight the differences in interaction between the glove films.

7.3.6 FTIR

FTIR was conducted on different regions of the gloves following the discovery of an adsorbed substance on the surface by the AFM. FTIR analysis was conducted using a Brucker ATR-FTIR instrument. Each sample was scanned 26 times in the 550-4000 cm^{-1} region with a resolution of 4 cm^{-1}. FTIR was conducted on both of the gloves in 3 separate regions.

7.3.7 Data and statistical analysis

Data was processed as in previous chapters, calculating the resultant horizontal force to account to for misalignment when sliding the finger down the tools (Equation 4.2) and then the friction coefficients calculated via Equation 4.3. The data was processed to a power fit law, also described in Chapter 4 (Equation 4.4). Data was analysed using a two-tailed paired t-test to test for statistical significance. As the aim of this study is to evaluate whether the glove friction is affected by each contaminant, paired (two-tailed) t-tests were performed to compare the frictional of differences between the contaminant and the dry gloves. In conjunction with this, NBR and NRL gloves were also checked for differences, in order to establish any behavioural variations between the two gloves when contaminated. The alpha value for determining whether a result is statistically significant is set at $\alpha=0.05$. Therefore, a probability of difference value (p) should be less than 0.05 to be defined as statistically significant.

7.4 Results

7.4.1 Surface roughness and AFM of gloves

Three images are shown for each AFM sample, which represent the different types of scanning. In the height images, the brighter areas denote higher sections of the sample. In amplitude error, the brighter areas indicate a greater amplitude error, and in the phase mode, a brighter area indicates less viscous portions of the sample.

Figure 7.4 (a-c) shows a selection of the height, amplitude error and phase measurements of the outer surface of the NBR gloves and NRL is shown in Figure 7.5 (a-c). The results of the topography (height) show smaller clusters of the NBR compounds, whereas NRL shows larger clusters with bigger gaps between the groups of latex rubber. The gaps are possibly due to the differences in the patterns of the gloves, created during the manufacturing process. The NBR has a fixed random bump pattern manufactured at the fingertip, similar to the NBR gloves described in Chapter 6. The NRL gloves have a textured surface all the way around the glove, which is not too dissimilar from the NBR, also noted in Chapter 6.

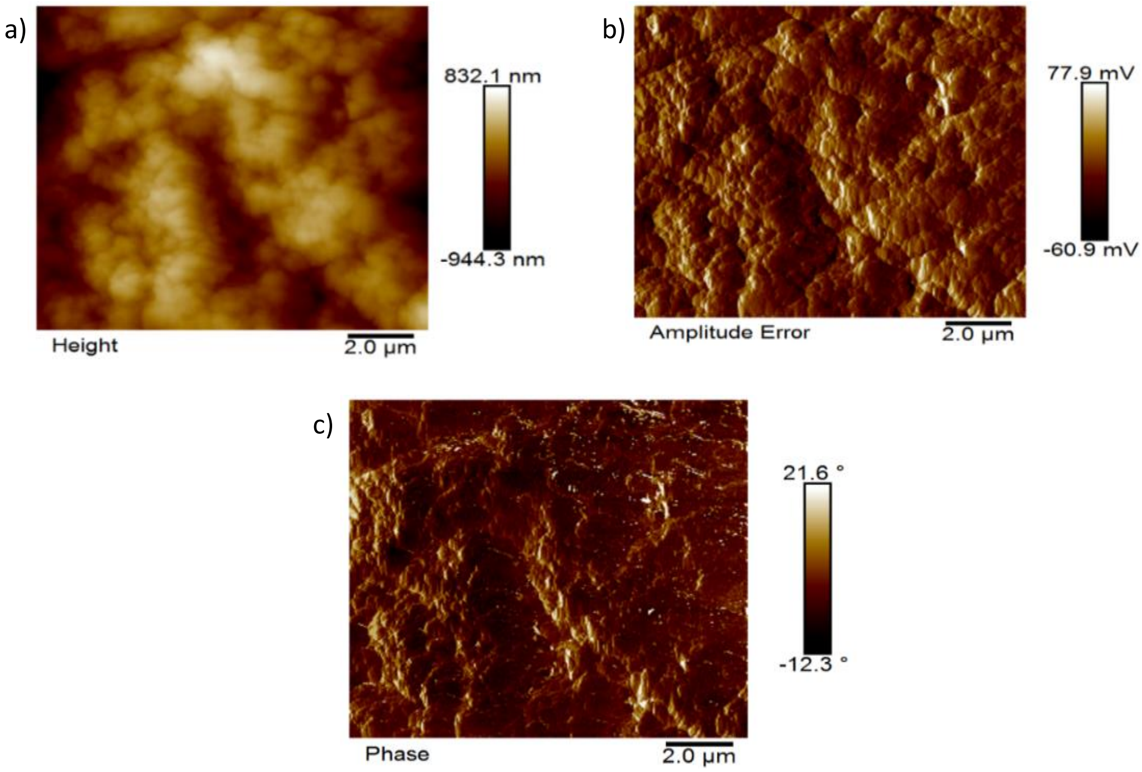


Figure 7.4 (a-c). AFM images of NBR glove showing height (a), amplitude error (b), and phase (c) images.

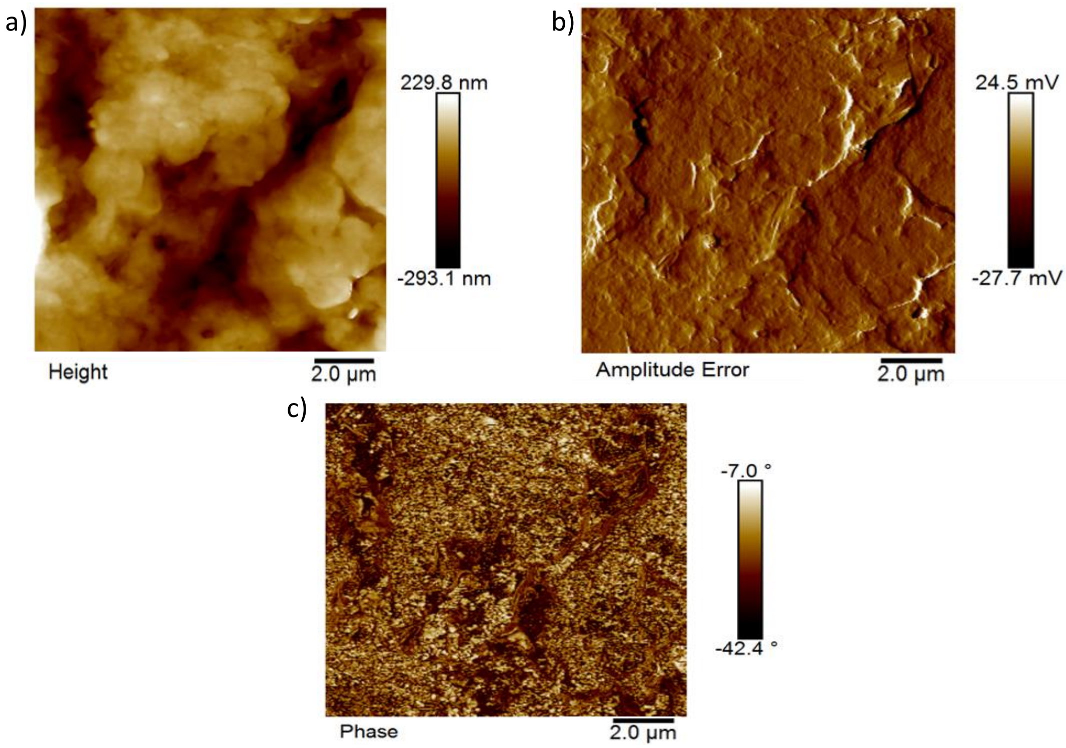


Figure 7.5 (a-c). AFM images of NRL glove showing height (a), amplitude error (b), and phase (c) images.

Adsorption

Where the interaction between the cantilever and the surface of the sample changes, there will be a change in the resonance frequency of the AFM instrument. For forces where more attraction is present, the frequency will be lower. For the forces where more repulsion is present, the frequency will be higher. Thus, the phase image allows for visualisation of the changes in properties of the material. Due to the nature of the attraction-repulsion forces of the AFM cantilever, any material property will show as a difference in the image (dissipation, adsorption, viscoelasticity, stiffness, adhesion) (242). Therefore, the phase images must be read with some caution (243). Nevertheless, a noticeable feature on both the NBR (Figure 7.6) and NRL (Figure 7.7) AFM scans was the presence of a possible adsorbed layer on the sample surface. Where the topographical image (height) shows a lighter section (higher) and the phase image shows a darker area (lower) this indicates the presence of liquid or gas adsorbed onto the material (244). In the NBR particularly, there are areas where 'smearing' is present (as is visible in Figure 7.6 b). Therefore, it was thought this was a result of contamination. As stated in the method, three samples of each glove were analysed, and this smearing and adsorption was noted in all three. Gloves were cleaned with nitrogen gas to remove any contaminants prior to analysis; however, this does not remove the presence of contaminants from handling, although gloves were worn. Figures 7.8 (NBR) and 7.9 (NRL) show the inner surface of the gloves. These also show the difference in phases seen on the outer gloves. In the NBR, this possible adsorption appears more in localised areas, rather than smeared as in Figure 7.6. The NRL, however, shows some similarities to the outer surface, however there are smaller, more frequent lighter areas (Figure 7.9).

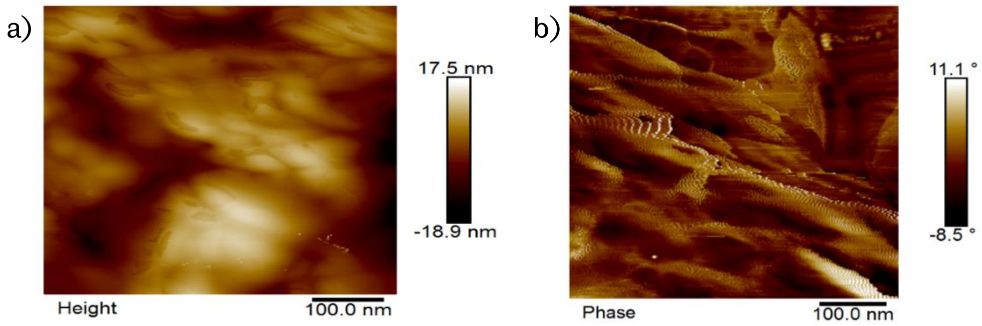


Figure 7.6. Height (a) and phase (b) images of the outer side of the NBR glove section showing the possible adsorption onto surface. Area of smearing has been highlighted.

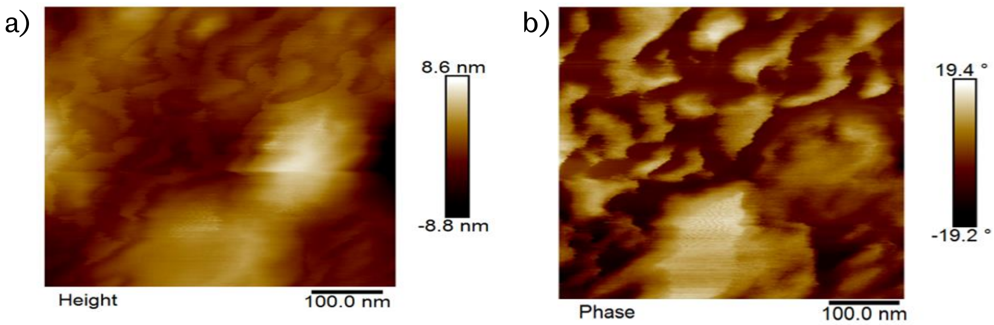


Figure 7.7. Height (a) and phase (b) images of the outer side of the NRL glove section showing the possible adsorption onto surface.

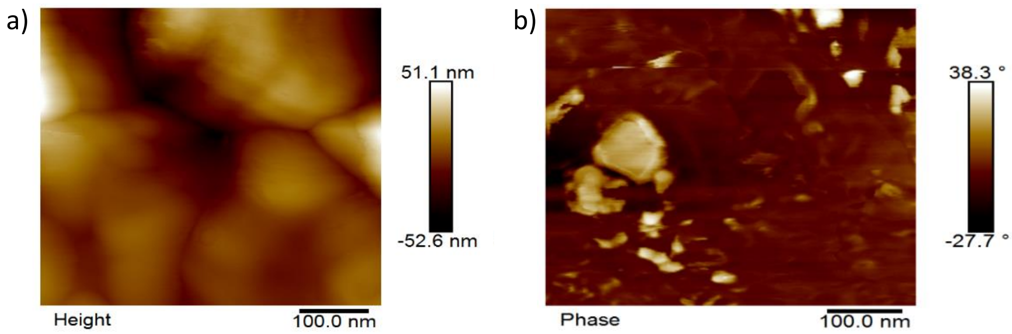


Figure 7.8. Height (a) and phase (b) images of the inner side of the NBR glove section showing the possible adsorption onto surface.

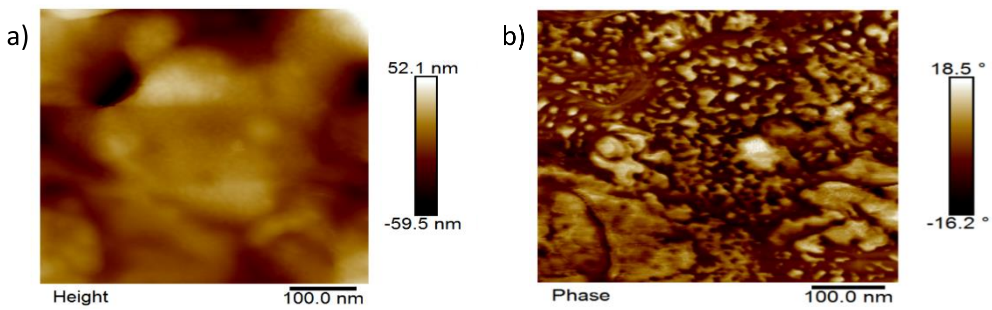


Figure 7.9. Height (a) and phase (b) images of the inner side of the NRL glove section showing the possible adsorption onto surface.

Adsorption identification

Visual analysis

Upon visual examination of the gloves, it can be seen that the gloves are not homogenous in colour. In essence, the gloves are not one solid shade of colour and show regions which are darker/lighter. In some cases, the differences are visible as dried drips. Figure 7.10 shows areas (around 25 cm^2) of the gloves where there are differences in light transparency when held up against a light source. The images have been saturated and overexposed in order to highlight these differences (NBR: +40 brightness, -40 contrast and +200% saturation; NRL: +30 brightness, -20 contrast and +400% saturation). Images are shown which are similar to the AFM phase mode in terms of contrast, clearly indicating the presence of different adsorbed substances onto the surface.

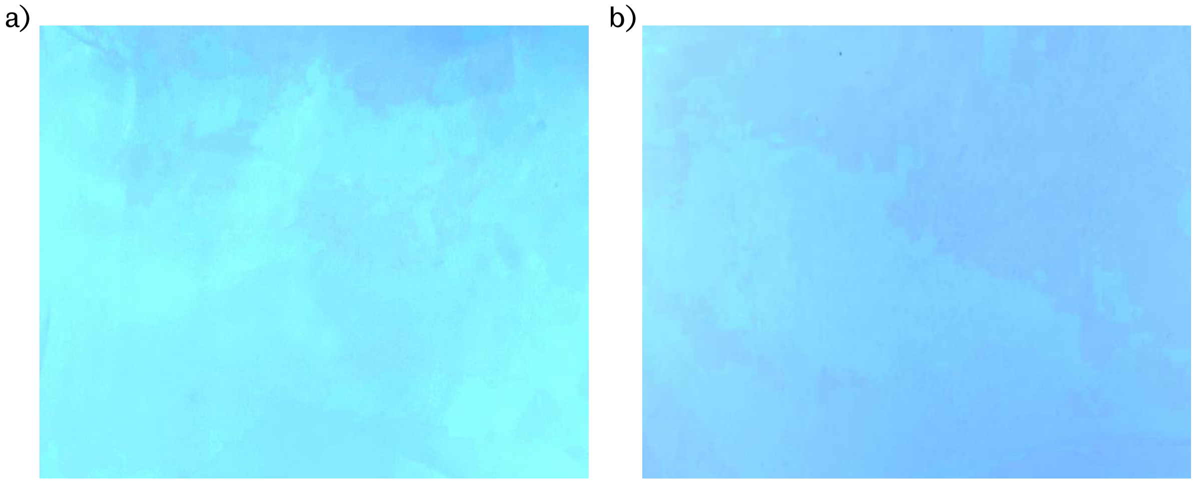


Figure 7.10. Difference in NBR and NRL films when exposed to light. a) NBR, colour correction +40 brightness, -40 contrast and +200% saturation and b) NRL, +30 brightness, -20 contrast and +400% saturation.

FTIR

In an attempt to identify the suspected adsorbed substance, FTIR was conducted on the gloves in 3 separate regions. The FTIR analysis was targeted on different places of the glove, ensuring the visible 'drips' noted were captured in the scans. No measurable variations are seen in the spectra (Figure 7.11).

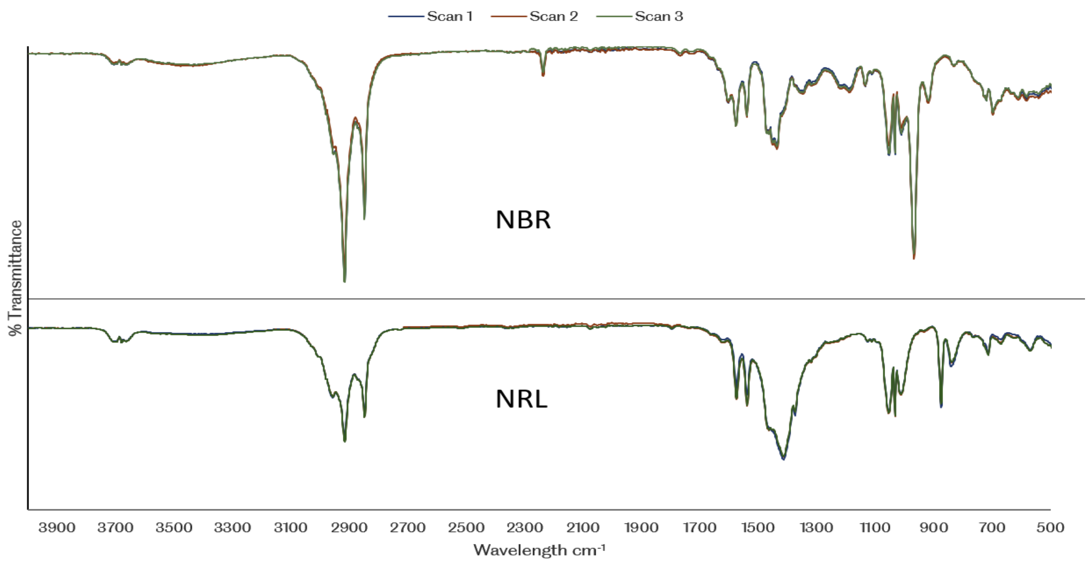


Figure 7.11. FTIR of NRL and NBR outer layers assessing for differences between scans.

Localised roughness

The AFM shows clusters of the core materials, with deep grooves between them. These grooves on the NBR are less deep, with an average depth of 60.71 (±13.43) nm, whereas NRL has grooves with depths of 151.88 (±4.78) nm. The clusters of materials were also scanned to assess the localised roughness. Figure 7.12 shows a typical roughness of the NBR sample (Ra=6.89 (±0.13) nm) and Figure 7.13 shows a profile of the NRL roughness (Ra=10.72 (±1.19) nm). It is important to note, this is only a 2 µm section shown. Therefore, the roughness differences shown are only on a small scale. Of the three scans taken, roughness measurements were taken on the 2 µm samples only, as these gave the clearest images for measurements.

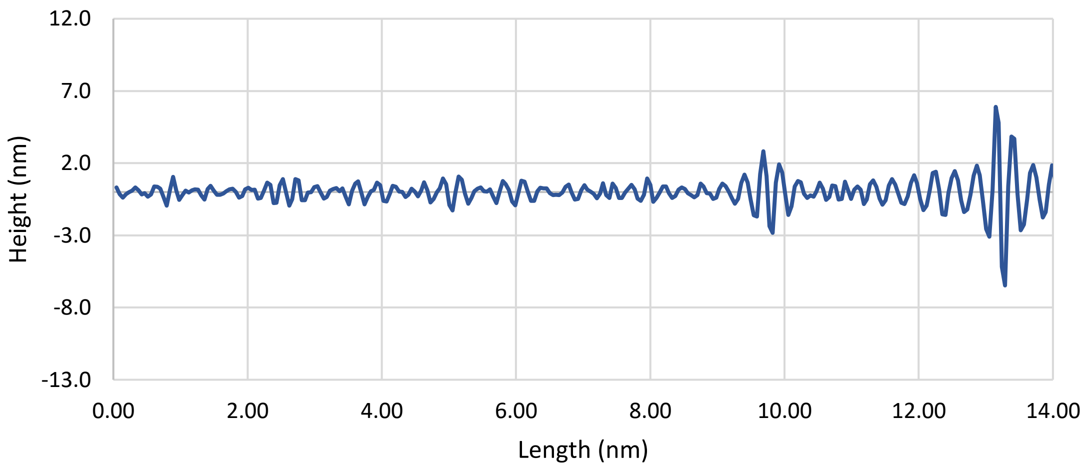


Figure 7.12. AFM roughness profile of NBR glove section

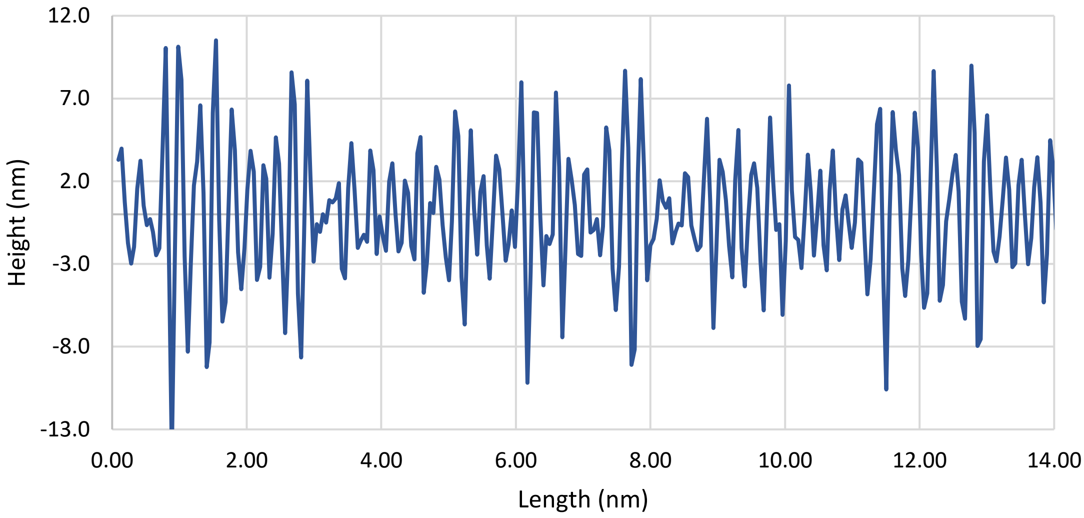


Figure 7.13. AFM roughness profile NRL glove section.

Surface roughness

The surface roughness scans using the 3D measurement instrument shows the average film roughness on a greater scale. Both of the gloves are shown to have similar surface roughness. NBR has a S_a of 1.83 (±0.27) µm, whereas NRL is slightly rougher with a S_a of 1.90 (±0.25) µm. Samples of the scans are shown in Figure 7.14. Although the gloves show similar Sa, the patterns on the glove are visually different. The NRL has a more concave nature of grooves, whereas the NBR appears more textured.

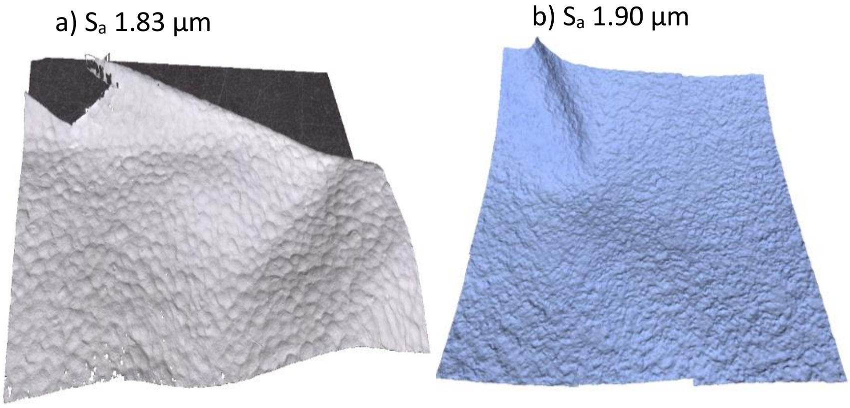


Figure 7.14. Surface roughness (Sa) of NRL (a) and NBR (b) gloves.

7.4.2 Contaminant characterisation

The viscosities of the contaminants can be found in Table 7.3. The lower end of the viscosity ranges from very low at 0.90 mPa-s with water to 7.25 mPa-s with the mixture solution. The highest noted viscosity is the oil at 70.10 mPa-s. Also, in Table 7.3 is the estimated film thickness. The NBR material is most likely to allow a thicker film to develop (with the exception of the alcohol, NBR t=2.40 µm; NRL t= 2.59 µm). This is also indicated from the results of the mass transfer used to calculate the film thickness, which are shown in Figure 7.15. In the mass transfer, it is shown that more substance is deposited on the NBR material, indicating higher affinity for the material over the NRL. All data was found to be within a normal distribution via the Shapiro-Wilk test for normality (192). The results show that the oil gives the greatest mass transfer, and the greatest film thickness (NBR mass= 0.14 (±0.006) g, t=5.74 µm; NRL mass=0.12 g (±0.005), t=5.00 µm). With exception of the powder, the alcohol shows the lowest transfer of substance for both NBR and NRL gloves. This also leads to the lowest estimated film thickness.

Table 7.3. Viscosity (η), density (*ρ*), and estimated film thickness (t) of fluid contaminants.

Contaminant	**η (mPa-s)**	***ρ* (kg/M^3)**	**t (µm)**	
			NBR	**NRL**
Alcohol	1.02 (±0.01)	814.69 (±0.05)	2.40	2.59
Mucin	3.13 (±0.05)	1085.25 (±1.09)	4.40	3.64
Oil	70.10 (±0.01)	929.95 (±0.06)	5.74	5.00
Water	0.90 (±0.01)	984.32 (±0.06)	2.84	2.76
Mixture	7.25 (±0.05)	1007.91 (±0.05)	4.82	3.43

± denotes standard deviation

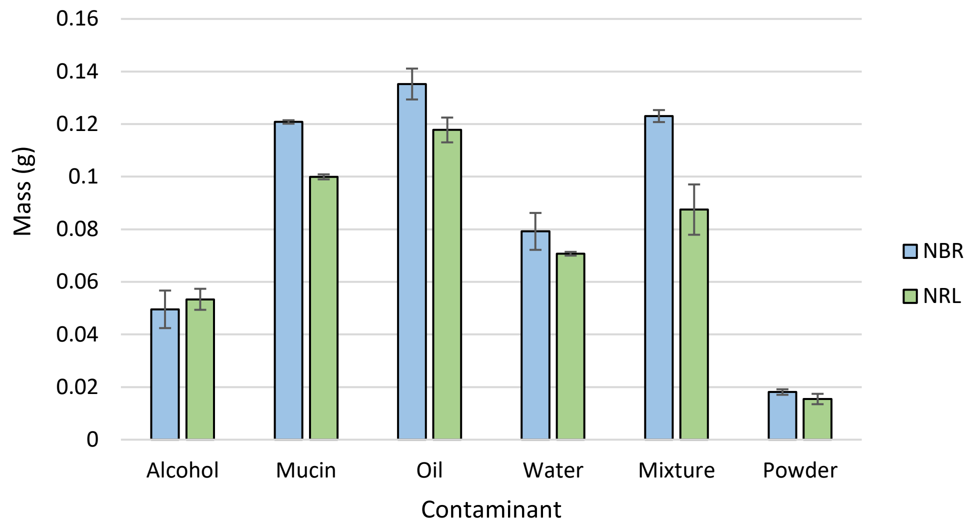


Figure 7.15. Weight of contaminants deposited onto the gloves. Error bars indicate standard deviation.

Contact angle

Figure 7.16 shows the results of the contact angles of the fluid contaminants with both glove films. With the exception of alcohol, all contaminants show a high surface wetting with NBR (low contact angle) and a low surface wetting (high contact angle) with NRL. The alcohol, however, shows to have a similar, low contact angle and high surface wetting of both samples (NBR= 21.67°, ±3.06; NRL= 22.33°, ±5.13). These were shown to be statistically similar following a paired two tailed t-test ($t(2)=-0.193$, *p=.886)*.

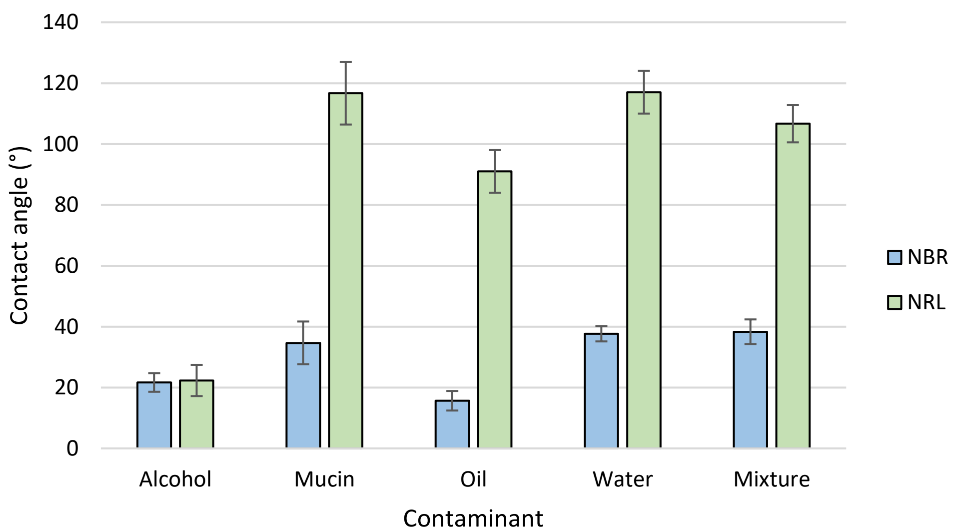


Figure 7.16. Contact angles of contaminants on the NBR and NRL material. Error bars indicate standard deviation

7.4.3 Friction

Over the load range it was discovered there was little difference between the coefficient of friction (CoF) at the minimum and maximum normal force applied for many of the contaminants, most notably in the NBR gloves. For this reason, and for simplicity in data presentation, only the CoFs at the minimum (~1 N) and maximum (~5 N) normal forces are displayed. CoFs at each load for each tool and contaminant can be found in the appendix, Section D.

NBR

In all of the tests conducted, the friction was found to increase with an increasing normal force. The CoF at minimum and maximum normal force for all of the tools and contaminants with NBR are shown in Figure 7.17. The t-test results comparing contaminant to the dry CoF are shown in Table 7.4. With the exception of tools 5 and 7, there is little change exhibited between the dry condition with some of the contaminants. However, there is a noticeable increase in CoF when compared to the contaminated friction. Statistical significance is shown between the dry condition and all other conditions in tools 5, 6, and 7 ($p<.05$). In tools 1-5 the water produces the lowest CoF, with the lowest being observed in tool 5 at the maximum normal force ($\mu = 0.19 \pm 0.03$), however there is little overall trend in which contaminant produces the greatest friction. Tools 1-4 show a more clustered variation in the results between the contaminants, indicating little difference in friction behaviour with notable exceptions (such as the mucin in tool 1), however there are many significant differences seen from the dry condition ($p<.05$). There is no contaminant which shows consistently significant differences from the dry condition. However, the greatest differences between the dry gloves and the contaminants are shown in tools 5 and 7, where contaminants are shown to greatly decrease the frictional properties of the gloves ($p<.05$). This is also observable in tools 4 and 6, but to a lesser extent. In general, the CoFs exhibit slight changes over the increasing loads, however these are not greatly different in many of the cases.

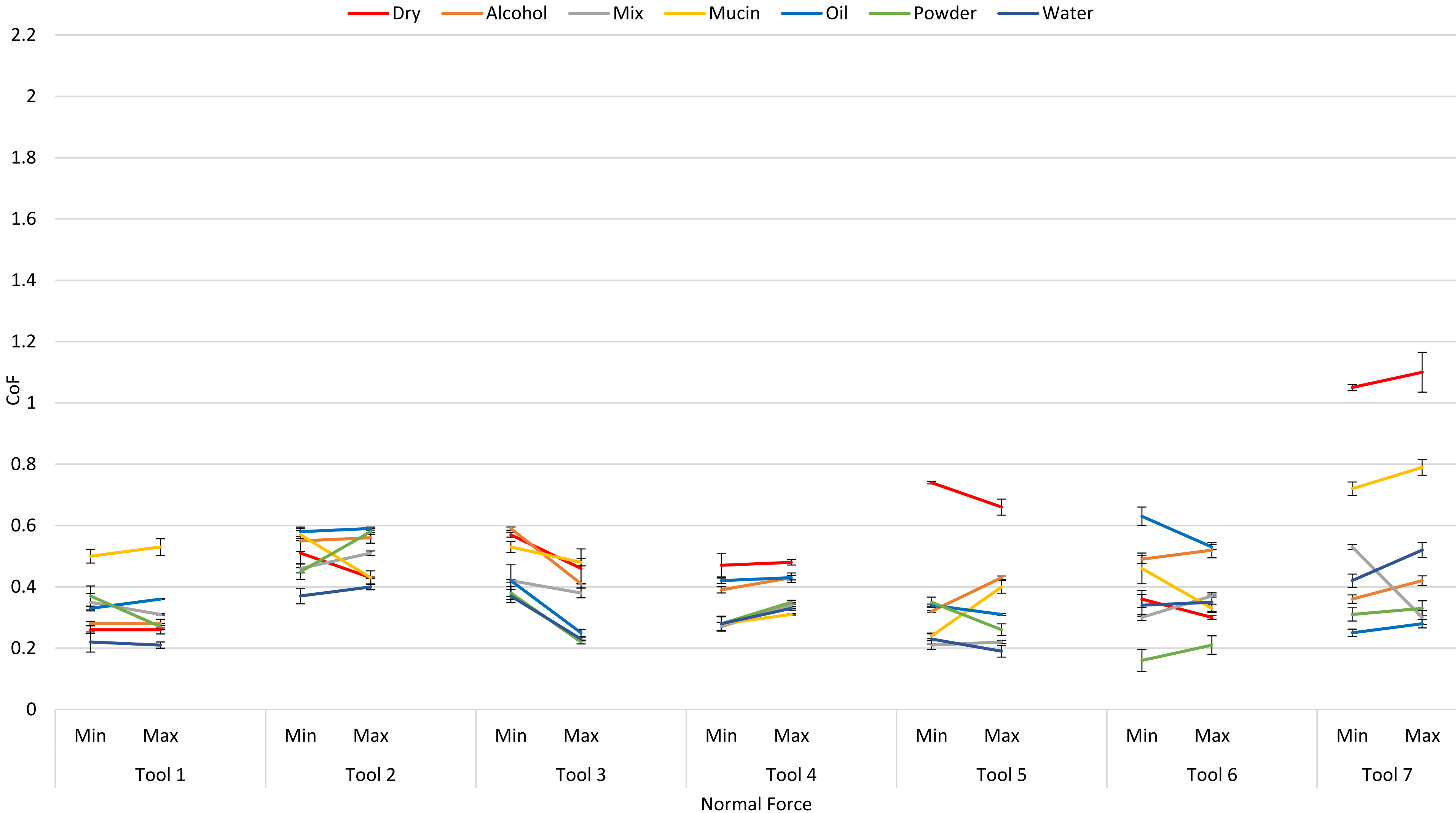


Figure 7.17. CoFs at the minimum (min) and maximum (max) normal forces applied with the NBR gloves in dry and contaminated conditions with each tool. Error bars denote standard error in the obtained CoFs.

Table 7.4. Results of t-tests comparing CoFs of contaminants to the dry NBR glove at the minimum (~1 N) and maximum (~5 N) normal forces.

Contaminant	Normal Force	Tool 1	Tool 2	Tool 3	Tool 4	Tool 5	Tool 6	Tool 7
Alcohol	**min**	*t(2)=6.288 p=.002**	*t(2)=-1.172 p=.153*	*t(2)=-2.345 p=.039**	*t(2)=-7.620 p=.001**	*t(2)=-21.357 p=<.001**	*t(2)=-19.451 p=<.001**	*t(2)=20.667 p=<.001**
	max	*t(2)=-1.546 p=.099*	*t(2)=-8.255 p=.001**	*t(2)=8.877 p=.023**	*t(2)=1.228 p=.143*	*t(2)=35.554 p=<.001**	*t(2)=-14.569 p=<.001**	*t(2)=23.305 p=<.001**
Mucin	**min**	*t(2)=-48.932 p=<.001**	*t(2)=-1.665 p=.086*	*t(2)=1.600 p=.092*	*t(2)=24.419 p=<.001**	*t(2)=26.685 p=<.001**	*t(2)=-3.089 p=<.018**	*t(2)=11.895 p=<.001**
	max	*t(2)=-64.383 p=<.001**	*t(2)=-0.930 p=.203*	*t(2)=-1.380 p=.120*	*t(2)=4.274 p=.006**	*t(2)=36.518 p=<.001**	*t(2)=-2.345 p=<.039**	*t(2)=11.771 p=<.001**
Oil	**min**	*t(2)=-5.265 p=.003**	*t(2)=-2.334 p=.040**	*t(2)=3.302 p=.015**	*t(2)=9.67 p=<.001**	*t(2)=16.406 p=<.001**	*t(2)=-6.513 p=<.001**	*t(2)=25.134 p=<.001**
	max	*t(2)=-26.169 p=<.001**	*t(2)=26.144 p=<.001**	*t(2)=1.439 p=<.001**	*t(2)=1.094 p=.168*	*t(2)=22.458 p=<.001**	*t(2)=-13.795 p=<.001**	*t(2)=14.983 p=<.001**
Powder	**min**	*t(2)=-2.604 p=.030**	*t(2)=1.550 p=.098*	*t(2)=3.491 p=.013**	*t(2)=5.100 p=<.001**	*t(2)=11.930 p=<.001**	*t(2)=17.413 p=<.001**	*t(2)=33.788 p=<.001**
	max	*t(2)=0.751 p=.247*	*t(2)=19.922 p=<.001**	*t(2)=31.616 p=<.001**	*t(2)=3.715 p=<.001**	*t(2)=29.297 p=<.001**	*t(2)=8.317 p=<.001**	*t(2)=27.290 p=<.001**
Water	**min**	*t(2)=0.899 p=.210*	*t(2)=2.787 p=.025**	*t(2)=11.284 p=<.001**	*t(2)=15.145 p=<.001**	*t(2)=27.693 p=<.001**	*t(2)=3.030 p=<.019**	*t(2)=33.788 p=<.001**
	max	*t(2)=11.224 p=<.001**	*t(2)=1.342 p=.125*	*t(2)=15.415 p=<.001**	*t(2)=4.025 p=.008**	*t(2)=72.825 p=<.001**	*t(2)=8.317 p=<.002**	*t(2)=20.238 p=<.001**
Mixture	**min**	*t(2)=-2.632 p=.029**	*t(2)=-1.558 p=.097*	*t(2)=10.349 p=<.001**	*t(2)=11.791 p=<.001**	*t(2)=21.584 p=<.001**	*t(2)=17.193 p=<.001**	*t(2)=21.220 p=<.001**
	max	*t(2)=-9.898 p=<.001**	*t(2)=-7.341 p=.001**	*t(2)=10.276 p=<.001**	*t(2)=3.360 p=.014**	*t(2)=38.824 p=<.001**	*t(2)=-4.825 p=<.004**	*t(2)=25.357 p=<.001**

**denotes statistical significance p<.05*

NRL

In all cases, with all contaminants and tools, the friction force increased with an increase in load with both gloves. The CoFs at the minimum and maximum normal force applied for all of the tools with NRL are shown in Figure 7.18. With the exception of tool 6, the dry condition has a greater CoF than when contaminants are added. Large variations in CoFs are observed with the dry conditions over the load range. Tool 1 is the only tool were the CoF increases with the increasing load, whereas the CoF decreases over the load range with the other tools. When contaminants are present, mucin induces more friction than the other contaminants, with higher friction coefficients observed for tools 2, 4, 5 and 6. Water is also observed to have higher friction than the other contaminants in tool 1 and is highest in tool 7 (μ at minimum normal force= 1.28 ±0.03; μ at maximum normal force= 1.31 ±0.03). Water and mucin exhibit similar CoFs over the loads with tool 3, and both produce the highest friction coefficients. Tools 3, 4 and 5 show small variations for the obtained CoFs, with similar ranges across the contaminants (μ=0.46-0.18). The CoFs however, do show slight changes in behaviour, such as water and mucin showing a decrease in CoF between minimum and maximum normal forces with tool 3, but increasing friction in tool 4 over the load range. In all of the tools used in this study, statistically significant differences are exhibited between each contaminant and the dry glove ($p<.001$, Table 7.5). Only one contaminant was found to be statistically similar to the dry condition is the water in Tool 6 at both the maximum (dry μ=0.97 ±0.02; water μ=0.99 ±0.02) and minimum (dry μ=1.03 ±0.02; water μ=0.97 ±0.05) normal forces. Mucin also shows similarities to the dry condition in tool 6 at the minimum force (mucin μ=1.10 ±0.06; $t(2)=-0.840$, $p=.224$). Although no clear trends are observed, there is a pattern of oil producing the lowest CoFs for each of the tools, and the mucin contaminant is generally of greater friction in 5 of the 7 pattern textures.

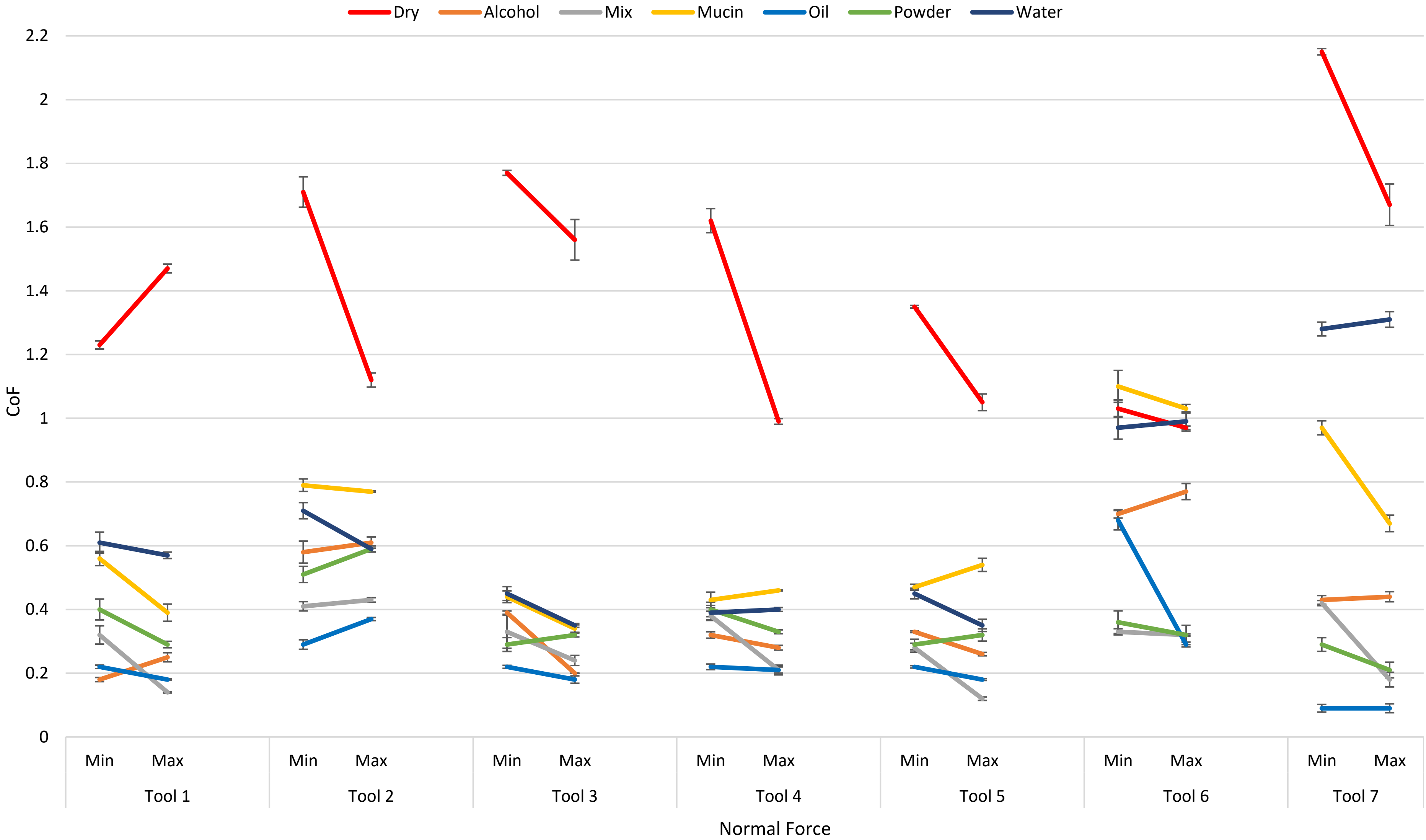


Figure 7.18. CoFs at the minimum (min) and maximum (max) normal forces applied with the NRL gloves in dry and contaminated conditions with each tool. Error bars denote standard error in the obtained CoFs.

Table 7.5. Results of t-tests comparing CoFs of contaminants to the dry NRL glove at the minimum (~1 N) and maximum (~5 N) normal forces.

Contaminant	Normal Force	Tool 1	Tool 2	Tool 3	Tool 4	Tool 5	Tool 6	Tool 7
Alcohol	**Min**	*t(2)=72.385 p=<.001**	*t(2)=17.959 p=<.001**	*t(2)=149.484 p=<.001**	*t(2)=31.998 p=<.001**	*t(2)=193.131 p=<.001**	*t(2)=9.203 p=<.001**	*t(2)=39.299 p=<.001**
	Max	*t(2)=62.638 p=<.001**	*t(2)=20.115 p=<.001**	*t(2)=20.905 p=<.001**	*t(2)=63.515 p=<.001**	*t(2)=30.516 p=<.001**	*t(2)=8.546 p=.001**	*t(2)=70.241 p=<.001**
Mucin	**Min**	*t(2)=27.899 p=<.001**	*t(2)=16.961 p=<.001**	*t(2)=28.314 p=<.001**	*t(2)=32.050 p=<.001**	*t(2)=69.464 p=<.001**	*t(2)=-0.840 p=.224*	*t(2)=39.768 p=<.001**
	Max	*t(2)=35.961 p=<.001**	*t(2)=17.488 p=<.001**	*t(2)=19.496 p=<.001**	*t(2)=61.744 p=<.001**	*t(2)=35.482 p=<.001**	*t(2)=-4.963 p=.004**	*t(2)=33.903 p=<.001**
Oil	**Min**	*t(2)=76.008 p=<.001**	*t(2)=27.445 p=<.001**	*t(2)=170.868 p=<.001**	*t(2)=35.157 p=<.001**	*t(2)=188.489 p=<.001**	*t(2)=9.005 p=<.001**	*t(2)=87.840 p=<.001**
	Max	*t(2)=92.196 p=<.001**	*t(2)=35.309 p=<.001**	*t(2)=20.495 p=<.001**	*t(2)=45.253 p=<.001**	*t(2)=34.512 p=<.001**	*t(2)=74.220 p=<.001**	*t(2)=103.418 p=<.001**
Powder	**Min**	*t(2)=45.321 p=<.001**	*t(2)=22.987 p=<.001**	*t(2)=64.026 p=<.001**	*t(2)=29.602 p=<.001**	*t(2)=177.797 p=<.001**	*t(2)=22.357 p=<.001**	*t(2)=71.882 p=<.001**
	Max	*t(2)=77.302 p=<.001**	*t(2)=13.482 p=<.001**	*t(2)=20.276 p=<.001**	*t(2)=34.720 p=<.001**	*t(2)=27.804 p=<.001**	*t(2)=105.939 p=<.001**	*t(2)=334.923 p=<.001**
Water	**Min**	*t(2)=17.081 p=<.001**	*t(2)=17.313 p=<.001**	*t(2)=58.469 p=<.001**	*t(2)=27.587 p=<.001**	*t(2)=48.554 p=<.001**	*t(2)=1.035 p=.180*	*t(2)=28.949 p=<.001**
	Max	*t(2)=53.224 p=<.001**	*t(2)=24.225 p=<.001**	*t(2)=20.003 p=<.001**	*t(2)=56.984 p=<.001**	*t(2)=22.365 p=<.001**	*t(2)=-1.272 p=.136*	*t(2)=11.282 p=<.001**
Mixture	**Min**	*t(2)=29.370 p=<.001**	*t(2)=24.807 p=<.001**	*t(2)=28.314 p=<.001**	*t(2)=32.050 p=<.001**	*t(2)=69.464 p=<.001**	*t(2)=24.257 p=<.001**	*t(2)=82.262 p=<.001**
	Max	*t(2)=96.434 p=<.001**	*t(2)=32.020 p=<.001**	*t(2)=19.496 p=<.001**	*t(2)=61.744 p=<.001**	*t(2)=35.482 p=<.001**	*t(2)=97.908 p=<.001**	*t(2)=6.647 p=<.001**

**denotes statistical significance p<.05*

Material comparison

Figure 7.19 shows the CoF at minimum and maximum normal force for both NRL and NBR gloves with contaminants (combined graphs of the above Figure 7.17 and 7.18). As can be see, there is little similarity between the CoFs of the contaminants. In tool 1, the powder contaminant does produce similar CoFs between the NBR (μ at minimum normal force= 0.37 ±0.04, μ at maximum normal force= 0.27 ±0.01) and the NRL (μ at minimum normal force= 0.39 ±0.01, μ at maximum normal force= 0.29 ±0.01). The lowest overall CoF is observed with NRL and oil on the smooth steel (μ= 0.09 ±0.02). A comparison of the averaged CoFs is presented in Table 7.6 along with statistical significance between the two gloves highlighted via paired t-tests. There are no observed statistically significant differences in tool 1 with the alcohol, mixture, mucin, and the powder at the minimum force. Indicating at a low load there is no significant difference in friction between these contaminants on either of the gloves ($p>.05$). The only occurrence of a contaminant not changing frictional properties between the two gloves, at the minimum and maximum normal force, was with alcohol when applied to tool 2, and powder applied to tool 1 ($p>.05$). As many of the comparisons show significant differences between the gloves, it is highlighted that there are likely differences in the contaminant interaction with the glove materials causing differences in frictional behaviour.

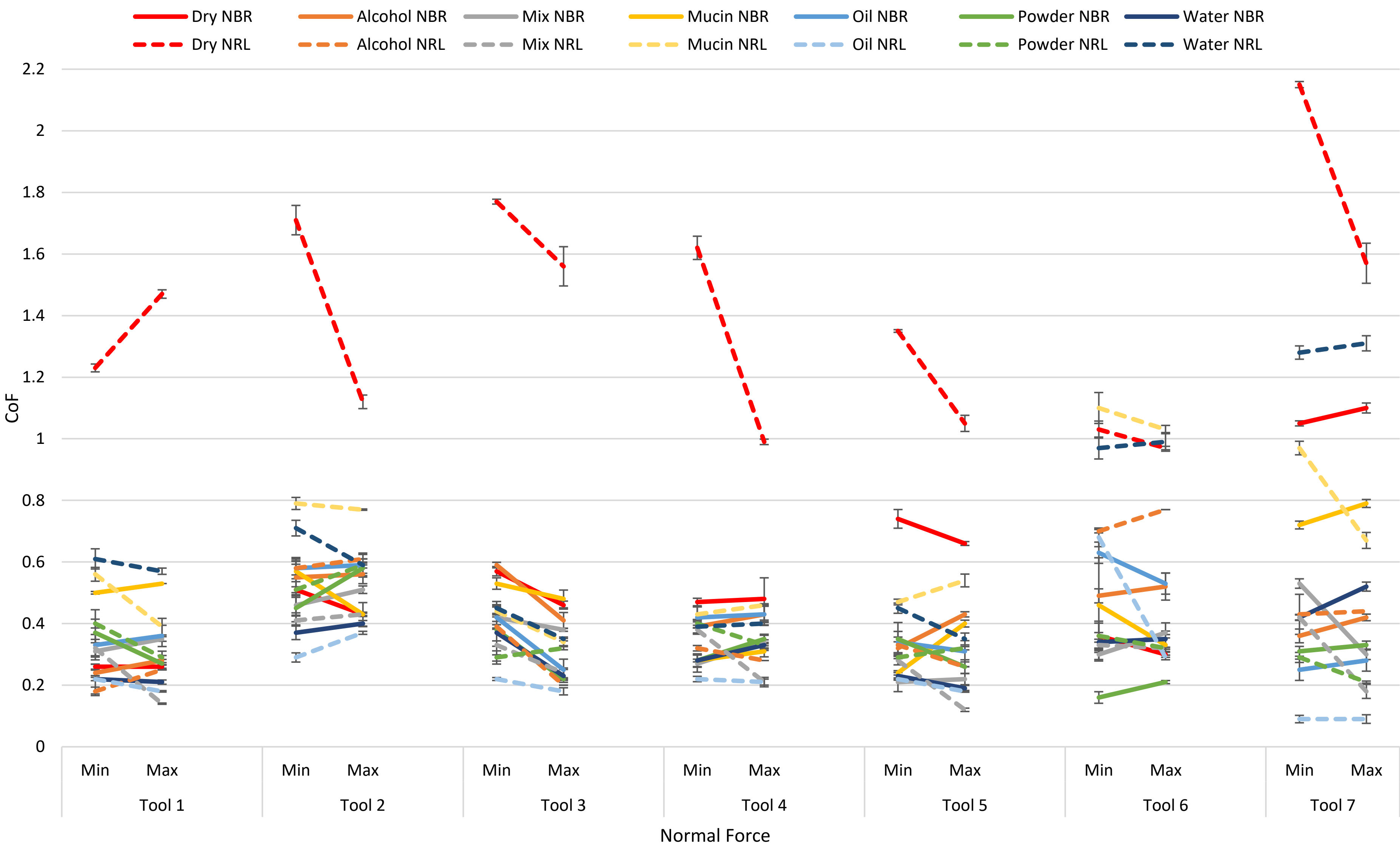


Figure 7.19. CoFs at the minimum (min) and maximum (max) normal forces applied both NBR and NRL gloves. NBR is represented by straight lines, whereas NRL is represented by dashed lines. Error bars denote standard deviation in the obtained friction coefficients.

Table 7.6. Average friction coefficient values obtained from each tool with the different contaminants used for the NRL and NBR gloves. Those highlighted in green show statistically significant differences between the two glove materials at the retrospective force (*p<.05*), whereas those in blue do not show any statistically significant differences between the two average friction coefficients (*p>.05*).

Condition	Friction Coefficient															
	Tool 1				Tool 2				Tool 3				Tool 4			
	Min force		Max force		Min force		Max force		Min force		Max force		Min force		Max force	
	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL
Dry	0.26	1.23	0.26	1.47	0.51	1.71	0.43	1.12	0.57	1.78	0.46	1.56	0.47	1.62	0.48	0.99
Alcohol	0.24	0.18	0.28	0.24	0.55	0.58	0.56	0.61	0.59	0.39	0.41	0.2	0.39	0.32	0.43	0.28
Mix	0.31	0.32	0.35	0.14	0.46	0.43	0.51	0.41	0.42	0.33	0.38	0.24	0.27	0.28	0.34	0.21
Mucin	0.5	0.56	0.53	0.39	0.57	0.78	0.43	0.77	0.53	0.44	0.48	0.34	0.28	0.43	0.31	0.46
Oil	0.33	0.22	0.36	0.18	0.58	0.29	0.59	0.37	0.42	0.22	0.25	0.22	0.42	0.22	0.43	0.21
Powder	0.37	0.39	0.27	0.29	0.45	0.51	0.58	0.59	0.38	0.29	0.22	0.24	0.28	0.39	0.35	0.34
Water	0.22	0.61	0.21	0.57	0.37	0.71	0.40	0.58	0.37	0.45	0.23	0.26	0.28	0.39	0.33	0.4

Condition	Friction Coefficient											
	Tool 5				Tool 6				Tool 7			
	Min force		Max force		Min force		Max force		Min force		Max force	
	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL
Dry	0.74	1.35	0.66	1.05	0.36	1.03	0.30	0.97	1.05	2.15	1.1	1.67
Alcohol	0.32	0.33	0.43	0.26	0.49	0.7	0.52	0.77	0.36	0.43	0.42	0.44
Mix	0.21	0.28	0.22	0.12	0.30	0.33	0.37	0.32	0.53	0.42	0.30	0.18
Mucin	0.24	0.47	0.40	0.54	0.46	1.1	0.33	1.03	0.72	0.97	0.79	0.67
Oil	0.34	0.22	0.31	0.18	0.63	0.68	0.53	0.29	0.25	0.09	0.28	0.09
Powder	0.35	0.29	0.26	0.32	0.16	0.36	0.21	0.32	0.31	0.29	0.33	0.21
Water	0.23	0.45	0.19	0.35	0.34	0.97	0.35	0.99	0.42	1.28	0.52	1.31

7.5 Discussion

7.5.1 AFM and roughness profile

There are similarities between the NRL and NBR materials. However, on the nano scale, a great difference in roughness is shown, with the NBR being half the roughness of the NRL. Between both of the glove films, there are clusters of the core compounds present with grooves in between these clusters. The grooves on the NBR are smaller and shallower than observed in the NRL. This clustering and size difference between particles is to be expected due to the reported particle size of NBR being smaller on average (0.1-1.0 µm) than the NRL material (0.3-2.0 µm) (14, 44, 45). It is possible the gaps present are the edges of the raised bumps pattern on the NRL gloves; however, they were present frequently throughout each scan. When looking at the roughness of the gloves on a greater scale (using the optical microscopy) the gloves are shown to have similar surface roughnesses. Thus, the frictional difference in the dry gloves is possibly a result of the material properties, as discussed in Chapter 6.

Adsorption

Noticeably on both the NBR and NRL scans, there is the presence of an adsorbed substance onto the films. The phase images of the NBR material are similar to images published by Zhao, Xiang, Tian, *et al.* (245) who looked at NBR composites, and used AFM to find localised regions of different co-polymers after dispersing in manufacturing. However, the images from Zhao et al. (245) are taken from 0.5 × 0.5 nm areas, which are incredibly small areas. As multiple gloves were scanned, and they all had the similar phase images, this study shows that there is likely to be an adsorbed layer on the surface. This leads to the inference that this is a result of the post film manufacturing (leaching, chlorination etc.) once the core film has been dipped. Therefore, it is reasonable to assume that the chlorine has been adsorbed onto the surface, as discussed in depth in Chapter 5. When chlorinating the gloves in industry, the gloves are also sometimes 'double chlorinated', exposing both the inside and the outside to the chlorination treatment. In the NRL material, this reduces the amount of extractable proteins, leading to a lower exposure to the latex protein which causes allergies (14). Furthermore, tumble washing is a method of chlorinating gloves, which would expose both sides of the gloves to the chlorine (51). However, it is well documented that the chlorination process deteriorates the gloves, and the smoother surface on the outer side of the gloves can lead to problems with gripping through the reduced surface roughness (16, 47, 51). As stated in the results, due to the sensitivity of the phase imaging measuring different properties, these differences in the

phase images could be due to mechanical properties, rather than chemical (e.g. slightly thicker regions of the gloves).
As no measurable variations are seen in the spectra (Figure 7.11), this indicates that the adsorbed substance is either:

- Inert to the glove (such as water used for washing after the chlorination step),
- In such a small quantity that it is immeasurable to the FTIR,

Or

- Not an adsorbed substance, but the film itself with varied, with inhomogeneous regions throughout which affect the material properties in these localised regions.

The results seen in the NRL AFM scans are similar to those seen in Ho and Khew (56) who used AFM to analyse the films at different stages of the vulcanisation process. Although phase images were not obtained, the authors indicate that the differences in surface topography is likely to be due to the diffusion of the vulcanising reagents. The authors suggest that pre-vulcanisation is good for cross-linking of the polymers and forming a smooth film, where the traditional vulcanising method cause uneven cross-linking. It is possible the AFM is measuring differences in the latex particle coalescence, and that is what is visible on the films simply exposed to light (Figure 7.10). Differences in surface chemistry could have a great influence on the contacting surfaces, however minor. Thus, there may be stronger localised attractions in certain areas of the gloves, which could give rise to the variations seen in the contact angle measurements and friction, which will ultimately affect the performance of gloves, as seen in Chapter 6.

7.5.2 Friction and effects of tool patterns

A study conducted by Laroche *et al.* (114), looking at the effects of glove friction on different tool patterns of a similar nature, found, on average, the friction of the NBR gloves was higher than the NRL. However, in this study, the opposite is observed in most of the tools. The study by Laroche *et al.* (114) only looked at the effects of water on the static friction, with no control (dry condition) and looked at higher normal forces (40 N). Furthermore, the study does not state whether the gloves were examination or surgical, which was indicated to be a factor in the frictional properties due to the bulk material properties in Chapter 6. Anwer (116) showed that blood and blood-water mixtures lowered friction with NRL gloves on a scalpel, which is observed with some of the contaminants in this study with the scalpel. As blood was not used in this study, the results cannot be compared directly, but will be discussions around blood friction can be found in Chapter 9.

In this study, few trends are observed with the contaminants through the various tools, although most differences are shown in the NRL gloves in dry condition and in smoother surfaces when mucin is applied. It was hoped there would be more observable trends in behaviour with each contaminant, in order to quantify how friction was affected in a consistent manner. This would better inform glove manufacturers on how their materials were responding to certain contaminants, allowing for a better targeted marketing with regards to frictional properties of gloves depending on their use. However, great frictional differences are apparent when the NBR and NRL gloves are in contact with different tool surfaces. Tool 2, with the annular deep ridged surface, produced a greater CoF with the contaminants in both of the glove materials. This was expected due to the deeper pattern (0.8mm) which will allow contaminants to fall into the gaps and prevent separation of the glove-tool surface. Therefore, contact area would be increased between the gloves and the metal. This is evidenced by the general increase in the CoF with both glove materials, except mucin and water, in which the CoF decreased as the load increased. It is likely that the differences in affinity for the materials leads to this increase in CoF, as well as the material behaviour, previously discussed in Chapter 6. The NRL gloves display greater CoFs than the NBR gloves, on average. It is also observed there is little change in CoF as the load increases with the dry NBR gloves, where NRL has much greater CoF changes over the loads with each tool. However, friction does increase with each load, but the friction is greater with the NRL material. In many of the gloves, it could be seen that the NRL was stretching during the movement of the glove down the tools, indicating the NRL material was getting trapped more in the grooves than the NBR material, as shown schematically in Figure 7.20. The less stiff NRL glove will depress more into the grooves and get stuck as the finger attempts to break the static friction and initiate sliding. This was demonstrated in Chapter 6 when discussing the asperity contact and deformation with the steel strip. In this study however, the bulk of the NRL material will be deforming on a macro level into the gaps of the tool treads, as well as at an asperity level. The stiffer NBR however, will glide easier over the material due to less deformation of the material into the gaps.

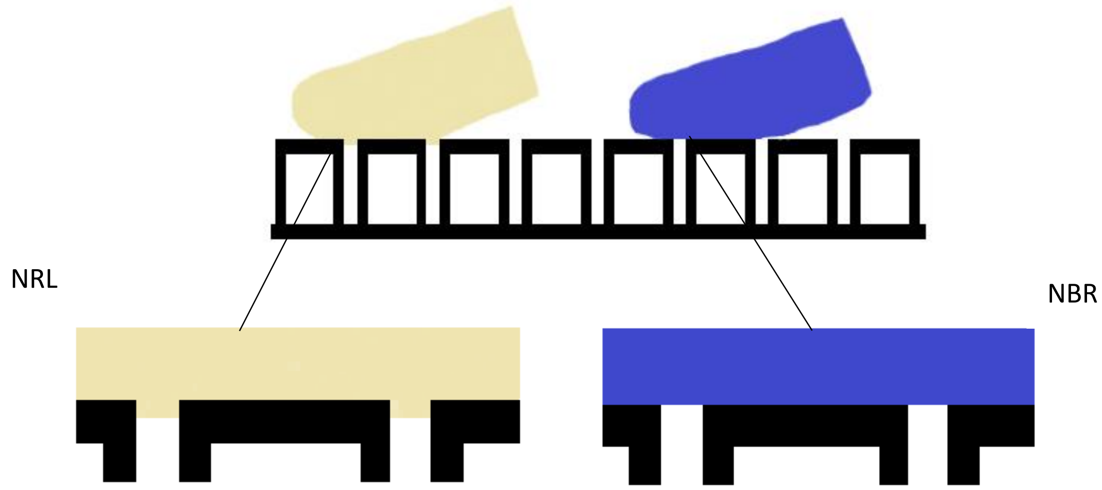


Figure 7.20. Deformation of gloves observed with tools. The lower stiffness of the NRL means the material fills the gap, incurring more static friction. The NBR material is stiffer and sits atop the close-gap tool pattern, incurring a lower static friction.

7.5.3 Contaminant interaction

Tools 1 and 5 have similar patterns with slightly differing depths and separation of patterns/wavelengths. However, the friction coefficients between the glove materials are different. This shows the effects the tread has on the presence of contaminants, as they will flow through the tread pattern upon contact, either increasing friction or decreasing friction. Tool 4 has a close-knit diamond pattern with a low tread depth, and little separation between the diamond tread. Overall, this tool shows to have the lowest average friction amongst the contaminants. Contact area is the likely reason for this decrease in friction. As the contaminants are introduced, the low depth tread will be quickly filled by the fluids or the powder. This will cause the contaminant to ride above the tread and ensure separation of the glove from the tool pattern, acting as an initial lubricant for the system (106, 246). The thickness of the contaminant film/the amount deposited onto the glove, as determined by the affinity and viscosity of the contaminant, will impact on how much separation occurs once the glove is in contact with the surface (247). For example, in the NRL, the more viscous oil tends to produce the lower friction but produces higher friction in many of the tools in the NBR. This difference is noted with most contaminants between the gloves. In the NBR gloves, the contaminants tend to show an increase in CoF with load, although in many cases, these are only small changes, whereas NRL tends to show a decrease over the load. However, this is not true for all contaminants. This is because of the way the contaminants are reacting on the surface. The contaminants show affinity for the NBR gloves but are repelled by the NRL. High contact angles from the contaminants with NRL indicate the contaminants are being pushed away as the force is increased, and friction decreases as the gaps are filled, as shown schematically in Figure 7.21. However, alcohol was found to have a good surface wettability of the NRL and produces varied results in friction across the tools.

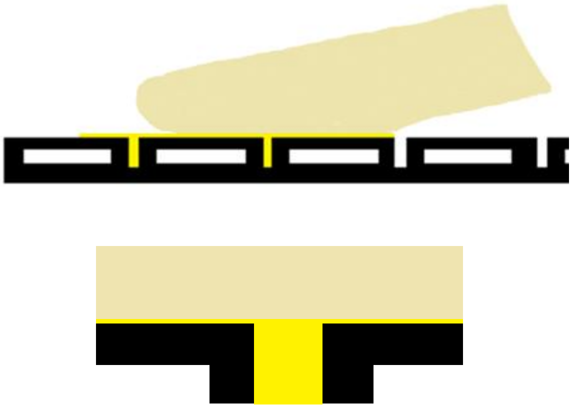


Figure 7.21. NRL reaction with tools with low tread depth. Contaminants fill gaps easier as repelled by the NRL material, this separates the glove from the surface, decreasing friction.

It is proposed that affinity and interaction with the gloves are the most important factors in whether the contaminants will affect friction. These chemical interactions determine how the contaminants behave on the gloves, as well as the prevalence of thicker films with different glove materials. In the mixture solution, CoFs are notably higher in NBR than the NRL (except tools 5 and 6). In addition, there are multiple differences in frictional behaviour between the materials. For example, in tool 4, the CoF in both gloves is the same at the minimum normal force (~1 N), but an increase in load causes an increase in CoF with the NBR material, but a decrease is observed with the NRL. During the application of the contaminants, the fingers were held into the solutions and moved around to encourage binding and interaction with the different components. Thus, differences in interaction with the distinct components will encourage variances in surface wettability, film thickness, and adherence of components to the gloves. This means, there was likely a difference in what constituents were attracted to the different gloves when the finger was removed from the solution.

Electrostatic interaction

The gloves possess slight surface charges and contact with both the metal and the contaminants can increase this charge potential. However, the influence of the charge increase is highly unpredictable (248). NBR films encompass a positive surface charge, with more polar characteristics, whilst the NRL film possess a negative surface charge with non-polar characteristics (14, 248, 249). Thus polymers such as the oil, composed of triglyceride fats, protein (mucin), and the mixed solution will have greater differences in reactions over the loads between gloves (233). This would have either a lubricating effect or increase adhesion properties of the contaminant, depending on the interaction with the glove film.

Mucin film development

Of all the contaminants used, mucin appears to consistently give the highest CoFs between the gloves with most of the tools. Previous studies have shown the development of mucoadhesive films on surfaces. These mucoadhesive films form as a result of interaction with the environment, causing proteins to fold in an loose water through self-assembly (250). This film development depends on the environmental conditions, such as temperature and interaction, as well as the viscosity and shear (233, 251, 252). Higher shear rates in a system have been shown to potentially elongate polymer chains, making the system more ordered, affecting the lubrication and adhesion properties of mucin (233, 253). The groups surrounding the core peptide (central protein) of the mucin are dominated by negatively charged carbohydrates. This gives an overall negative charge to the mucin structure at physiological pH (234), and is also the contaminant which contains greater differences in positive and negative domains (233), indicating the likelihood of differences in interaction with the two oppositely charged materials. In addition, mucin has been shown to have good wettability with different surface charges, such as the case with holding dentures (254). Together, the viscosity of the mucin along with surface wettability and film development can increase adhesive properties when handling equipment in a clinical setting (250). Great differences are observed with this protein between the glove materials. Overall, the friction of the NRL gloves is higher with mucin applied in tool 2, 3, and the smooth steel when compared to the mucin contaminated NBR. Furthermore, there is a larger decrease in friction with the NRL in tool 1 and tool 7, whereas an increase is observed with the NBR gloves with the mucin protein, indicating the nature of the protein behaviour is intrinsic to the frictional properties.

The adhesive and lubricious properties of the mucin are dependent upon the interaction with the gloves. Many oral tribology studies assessing mucin interactions study how the mucin interaction is dependent upon the charge and the environment (255, 256). The protein will naturally contort and respond to the environment it is put in. In this study, the interactions are based on the electrostatic attraction and repulsion between both the gloves, and the protein itself (233). The most dominant charge in mucin is the negatively charged carbohydrates, causing the negative charge of mucin to interact more with positive charges. Thus, the protein will have a greater interaction with the NBR gloves. Figure 7.22 indicates that the negatively charged mucin will be attracted to both the positively charged NBR and the positively charged surfaces (248, 249, 257).

This would bring the two surfaces together, increasing friction through both electrostatic interaction and possible increased asperity contact. The NRL will, however, feel more charge repulsion from the mucin, and the more positively charged regions of the core peptide will interact with the NRL, leading to a weaker interaction than with the NBR.

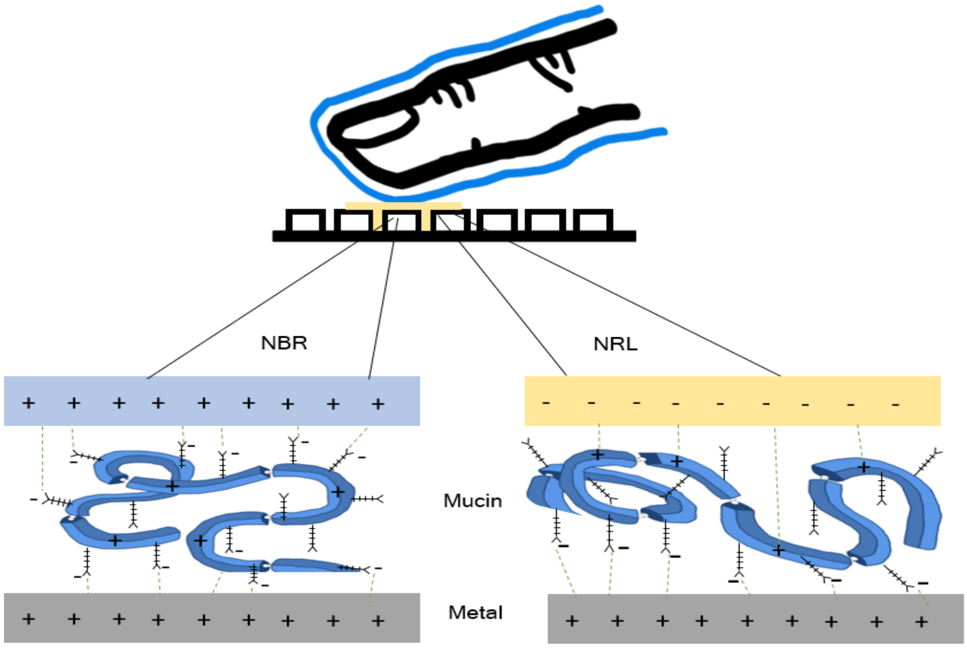


Figure 7.22. Proposed representation of the attraction of charges between mucin-steel and mucin-NBR and mucin-NRL.

In some cases the frictional properties of the NBR are decreased, such as the smoother tools (3, 4 and 7). This could be due to the interaction with the surfaces creating lubricating properties allowing less time for film formation. Previous work with mucin has highlighted that the film formation is more apparent on surfaces which have hydrophobic tendencies, such as the case in the NRL used in this study (251). This is likely to be the reason for a higher friction than other contaminants. It is proposed that the mucin has a higher affinity for the NBR, which causes a lubricating effect in some tools, and in others, causes friction through film formation and the materials being pulled together. On the other hand, the mucin is hydrophobically repelled from the NRL, causing surface separation and decreased friction. As the CoF of the dry glove is generally greater than the NBR gloves, this could be of a greater detriment to the glove user.

Film formation over time

Where these studies have been conducted, it must be kept in mind that the development of a mucoadhesive tribofilm is not instantaneous. To assess the change in possible confirmation of the proteins, the dynamic friction was checked. Figure 7.23 shows that at 5.02 N, after around 7 seconds, the friction of the NRL gloves steadily begins to increase on the smooth steel (tool 7). This is the likely to be the development of a mucoadhesive film brought about by shear stress on the mucin, and the slight affinity of the weakly positively charged metal surface (235, 252). This increase was apparent in both the NRL and NBR gloves but was more prominent in the NRL. Further tests would need to be conducted by holding the contaminated finger for longer on the surface before initiating the sliding. This would allow for a greater insight into the development of the film formation.

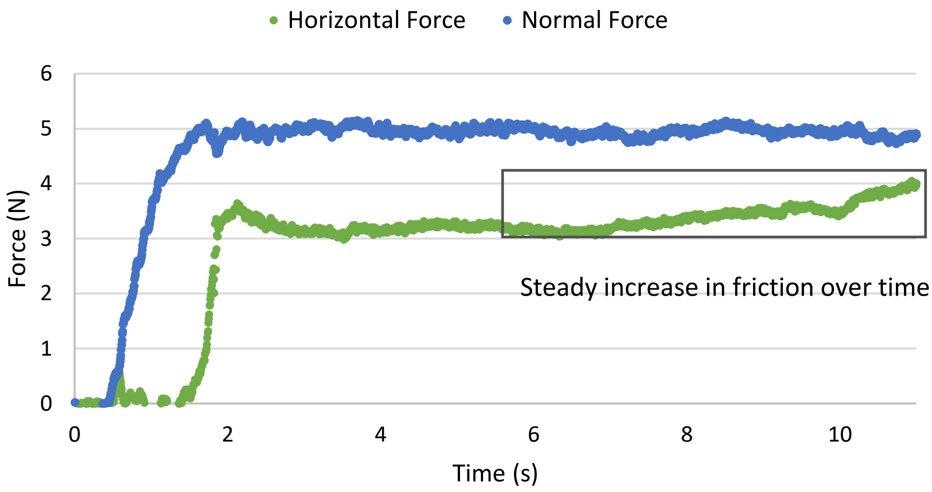


Figure 7.23. Example of film development over time for a NRL glove with mucin applied, sliding on steel.

Alcohol

The alcohol solution shows similar contact angles with both gloves with similar estimated film thicknesses. However, although a similar wettability was observed, the tribological properties of the gloves were still affected in different ways. This is likely due to the way in which the gloves are wetted, leading to different surface chemistry and interaction, as previously discussed with protein/polymers. The alcohol is composed of two key components, ethanol (C_2H_5OH) and chlorhexidine gluconate ($C_{22}H_{30}Cl_2N_{10}$). The hydroxyl group (OH) of the ethanol makes the compound strongly polar, which will cause the OH group to attract to the NBR glove. On the other hand, the ethyl group (C_2H_5) is non-polar, which will cause high wettability of the NRL surface (258). The chlorhexidine gluconate is a strongly polar compound, which will be dissolved in the alcohol and further add to the interaction with the polar NBR surface (259). As the gluconate is dissolved into ethanol, there will be interaction, albeit weakly, with the non-polar NRL surface. A similar effect has been noted with all contaminants. As different frictional properties, and behaviours are observed between the gloves, it is clear that knowledge of the affinity of the contaminants for the glove films is vital for assessing frictional behaviour.

Evaporation and flow

Evaporation would cause more contact between the surface pattern and the glove than with other contaminants. Although the gloves are of similar roughness, the NRL gloves are shown to have more concave grooves, whereas the NBR looks to possess more convex grooves. This was also noticed in the AFM images produced by Ho and Khew (56). The evaporation of the contaminant from the surface is most likely to occur with the alcohol solvent, which was also included in the mixed solution. This evaporation would be dependent on the airflow around the tool/glove and the time between the solution being removed from the stock and placed onto the finger. Due to the concave nature of the NRL pattern, as well as the deeper groves noted on the AFM, it is possible that when the finger is placed on the tools, there would be less evaporation as more of the contaminant is trapped in the deeper grooves. This would lead to a lower static friction, which is frequently observed in the NRL glove, as the surfaces remain separated for longer. However, not considered in this study, is that the fingers have some element of movement when gripping tools, the users may pick up and put down the tool's multiple times during use. This would, in effect, re-contaminate the tool and the gloves, and the contamination already stuck to the surfaces may cause different reactions on the surface.

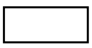
Influence of powder on friction

When the gloves are contaminated with powder, rather than a fluid, the friction, is on average, lower with the NBR gloves than the NRL. The lowest friction is observed when powder is present with tool 6 when NBR gloves were worn, indicating that the powder could cause slipping when holding disposable scalpels. For the frictional measurements with this tool, the finger was placed onto the circle in the centre of the tool pattern, which does not have any groves, which would maximise the contact area. The lower friction is due to the powder reducing contact area and separating the surfaces sufficiently to reduce the friction of the glove-surface contact, similar to that seen in Figure 7.21. This is also observed on the smooth steel (tool 7), which shows a greatly reduced friction with both gloves when the powder is present. In some instances, such as tools 4 and 6 with both gloves, there is an observed increase in CoF with increasing load. This could be due to the differences in powder stuck to the gloves or small areas of inhomogeneity in the powder.

The powder used in this study consists of talc, also known as hydrated magnesium silicate. As with the fluid contaminants discussed, the magnesium silicate contains domains that allow for both polar and non-polar interactions (260). Therefore, the powder will interact with both gloves. However, more powder was found to be stuck to the NBR than the NRL. Although the amount on the finger was small, and the difference between the two were found to be insignificant ($t(2)=-1.538$, *p=.541*). Furthermore, the results of the AFM indicate the differences in behaviour, observed primarily in tools 6 and 7, could be due to the variations in the way the gloves are being contaminated. In the NRL, the large latex rubber clusters cause deeper gaps to form between clusters, whereas the NBR is much smaller, and overall smoother. These smooth isolated regions may have an effect on the interaction with the powder. As there are larger clusters of the NRL material, there is surface interaction due to reduced isolated areas. However, more powder is likely to be trapped in larger gaps between these clusters. It is possible that minute weights of this powder fall out of these gaps upon contact/movement, which causes a reduction in friction by separation of the surfaces.

Table 7.7 summarises the increase or decrease in friction at a 1 N force, to ease visualisation of the effects the contaminants have on the gloves. In most cases, friction is reduced by the contaminants. Those where friction is greater than the dry glove occurs with the NBR material, primarily with alcohol and with tool 1, which has a low tread depth. Although similar in surface texture, tools 3 and 7 were different materials, and different widths, and therefore contact area, which gives rise to the differences in some of the frictional properties observed with the NBR.

Table 7.7. Summary of frictional differences to the dry glove at 1 N load, where ‘L’ = lower than the dry CoF, and ‘H’ = higher than the dry CoF.

	Alcohol		Mucin		Oil		Powder		Water		Mixture	
Pattern	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL	NBR	NRL
	H	L	H	L	H	L	H	L	L	L	H	L
	H	L	H	L	H	L	L	L	L	L	L	L
	H	L	L	L	L	L	L	L	L	L	L	L
	L	L	L	L	L	L	L	L	L	L	L	L
	L	L	L	L	L	L	L	L	L	L	L	L
	H	L	H	L	H	L	L	L	L	L	L	L
	L	L	L	L	L	L	L	L	L	L	L	L

7.6 Conclusions

The findings of this chapter are as follows:

- AFM of the glove films reveals the possibility of an adsorbed surface on the glove materials. This is thought to arise as a function of the chlorination of the glove materials during the manufacturing process and could impact the interaction of contaminants with the glove materials.
- It has been shown that friction can be modified upon exposure to the contaminants used in this study. NRL gloves were shown to be severely affected by contaminants, greatly reducing friction. On the other hand, NBR gloves were shown to have both increases and decreases in frictional properties, depending upon the tool pattern. The differences in the CoF of the contaminated materials, in many cases, are not greatly affected by an increase in load.
- The change in frictional behaviour is dependent on the affinity of the contaminant for the gloves, which modifies the ability to separate the surfaces and allows lubrication into the system. The thicker the film, the greater the initial separation, which would induce lower friction, which is observed in some cases in the NRL, which shows a poor surface wettability, with hydrophobic tendencies. On the other hand, the NBR shows a good surface wettability,

with hydrophilic characteristics. In addition to this initial film thickness, the chemical interactions have changed the way the contaminants interact with the gloves, causing great differences in the frictional properties between the two materials studied.

- The differences in frictional behaviour also depend on the tread pattern. Where the tools were smoother, the friction was reduced greater when contaminants were present at the maximum load.
- Differences in friction are likely to adversely affect grip in the NRL gloves, as decreases in friction are more observable than in the NBR when contaminated, indicating equipment is more likely to be near dropping/sipping from the user's fingers. The tools which exhibit higher friction coefficients will allow easier grip with less pinch force, which will in turn reduce hand fatigue.
- As it is understood that the frictional properties of the gloves are easily modified by the addition of contaminants, it needs to be identified as to how that impacts user performance. It could be that the small friction modifications that are present have no effect on the user, reducing the likelihood of problems occurring. However, the contaminants could change the perception of the glove user, changing their sensitivity and affecting their dexterity.

Chapter Eight: Effects of contamination on dexterity and sensitivity

At the forefront of the literature assessing medical gloves is dexterity and sensitivity. However, the inclusion of contaminants, making the assessments more relevant to realistic situations, have been neglected in the literature (6). Highlighted in Chapter 7 was the requirement for more performance assessments to be conducted in-situ. It was shown that the frictional properties of both NRL and NBR materials were affected by contamination from a variety of substances. In many cases, this lowered the frictional properties of the gloves, especially with the NRL gloves. This chapter explores this contamination further, assessing if, and how, contaminants affect the performance capabilities (dexterity and sensitivity) of the user (232).

8.1 Introduction

Understanding if the differences in frictional properties, observed in Chapter 7, influence the performance measures, such as dexterity and sensitivity, is vital to understanding the effects gloves have on the user. Stimuli changes on the fingers are a result of friction created by the deformation of skin. This deformation and friction create surface strains that propagate to mechanoreceptors, which are vital for sensory perception, allowing for physical feeling (63, 189). They also play a vital role in providing feedback regarding grasp. Therefore, the tactile sensation is also pivotal in preventing slipping and manipulation of objects (261). The presence of a contaminant on the gloves could affect tactile sensation by way of dampening the stimulus, which could lead to incorrect patient care through missed information or dropped equipment. Furthermore, external substances on the gloves could change the perception of the glove user, especially in cases where the contaminants are of a different temperature. This has been shown to affect the dexterity of participants when completing pegboard dexterity tasks (262).

8.2 Aim and objectives

The aim of this study is to assess to what extent glove user dexterity and sensitivity is affected by the contamination assessed in Chapter 7. Mucin has been chosen from the contaminants used in the previous chapter to contaminate the gloves. Due to the differences in frictional behaviour observed, mucin was perhaps the most intriguing due to the intrinsic nature of the protein. Specifically, porcine gastric mucin has been observed to display similar behaviour and viscosity to human mucin found in saliva (233, 254). This allows for conclusions to be drawn on how saliva/mucus in the body may influence the dexterity and sensitivity performance of the glove users. In Chapter 7, the mucin was shown to give different frictional properties for both of the gloves. This was due to the differences in behaviour of the polymer chains, the interactions with the tools, and ultimately the reactions with the glove films (233, 234, 250). Mucin is a long chain protein, surrounding by carbohydrate chains, which aid interaction through the contortion of proteins (233). This contortion happens due to the interaction with the glove material surfaces. The negatively charged NRL repels the mucin, which aids mucoadhesive film formation over time. The positively charged NBR draws more mucin to the surface and causes differences in frictional properties when compared to the NRL (248, 249). Therefore, it is expected that there will be differences in dexterity and sensitivity performance due to the different way in which the gloves and mucin are interacting with the environment. In addition, out of the contaminants selected in Chapter 7, mucin is most likely to be contacted in a medical setting, given the contaminants discussed in Chapter 3 (233). Understanding the effects of contaminants on examination glove users is salient to comprehending whether contamination is detrimental to the tasks being carried out.

8.3 Materials and methods

8.3.1 Participants

A total of 15 participants (13 male and 2 female) took part in the dexterity tests, and 12 (10 male and 2 female) took part in the sensitivity tests. All participants were asked if they had any sensorimotor deficiencies, any allergies to latex, or any conditions that could affect their sensitivity or dexterity. All participants were recruited from The University of Sheffield and were aged between 22 and 34 years (for both tests). Ethical approval was received by the Research Ethics Committee of the Department of Mechanical Engineering, University of Sheffield (No: 016619).

8.3.2 Glove selection and analysis

Participants donned the same glove make and model used in Chapter 7, for consistency. These were powder free, chlorinated NBR and NRL gloves, which were found to have similar thicknesses NBR= 0.106 (±0.006) mm; NRL= 0.114 (±0.007) mm). Participants were selected gloves based on their perceived “best-fit” (the glove size they would ordinarily use), however no measurements were taken of the hands for this section of work. Visual inspections were carried out to ensure gloves fit as expected. Gloves were expected to conform to the fingers and the hands with little to no areas of loose material, as described in Chapters 4, 5 and 6. The medium glove size was the “best-fit” choice for all participants with both glove materials, except for two who requested large NBR gloves but were comfortable with the medium NRL gloves.

FTIR

In Chapter 7, it was shown through contact angles, estimated film thickness, and the amount of mucin deposited onto the gloves, that the mucin has a stronger affinity for the NBR than the NRL, Therefore, to further assess if any surface binding takes place, FTIR was conducted. Samples were prepared by cutting off the fingertip of the glove (around 3 cm). Two samples were produced for each glove type: washed and unwashed. This allowed the determination of whether the surface has been cleaned by the water, or if the mucin has bonded/changed the surface chemistry. FTIR analysis was conducted using a Brucker ATR-FTIR instrument. Each sample was scanned 26 times in the 550-4000 cm^{-1} region with a resolution of 4 cm^{-1}. Two areas of each glove were analysed and averaged by OMNIC software. Using a Pasteur pipette, 1 ml of the mucin solution was placed onto the outer surface of each glove left for 10 minutes. The 'washed' sample was then held in a beaker of water (at 20-22^{o}C) and stirred for 10 seconds. The sample was then removed and left to out dry. The 'unwashed' sample was patted with a clean, dry tissue to remove any visible residue on the surface of the glove. Both washed and unwashed samples were left to dry for a minimum of 24 hours before analysis (16-24^{o}C). Each test was repeated three times for the NBR and NRL gloves (three washed samples and three unwashed samples). Three samples of each glove material were also analysed in an uncontaminated condition.

8.3.3 Dexterity measurements

Gross dexterity

Gross dexterity was measured using the Purdue pegboard, as discussed, and used in Chapter 6 (see Section 6.3.3). This was chosen in line with the previous reasons, the ease of implementation of the test to be used in industry, the ease of results comparison, and the ease of the test to be conducted by participants. As in the previous pegboard test, the participants completed all four tasks, which was split into two scores (combined and assembly test). The combined test consists of the number of pins placed in thirty seconds using the left hand, right hand and both hands (1.5 minutes in total). The assembly test consisted of the number of parts assembled in the pin-washer-collar-washer structure within the 1 minute allocated time. Participants who dropped pins, or assembly parts, were instructed to leave them and then pick up another for their allocated dish, so as not to waste time.

Fine dexterity

The Crawford Small Parts Dexterity Test (CSPDT) was chosen as an extra measurement of dexterity in this test. In medical tasks, fine dexterity using tweezers (and other tools) is salient to performance, thus assessing the effects of contaminants on the gloves with finer measurements would be insightful (114). As with the Purdue pegboard test, the board is small, and easy to use as well as implement into industry. The CSPDT, designed by Crawford and Crawford (263), has been discussed in Chapter 2 as a common test used for glove performance assessments (see Section 2.6.2). This test consists of two parts: pin and collar placement and screws placement. For this study, only the pin and collar test were chosen to be conducted, for both the constriction of time and the relevance to medical glove users in clinical practice.

The pin and collar test consists of a board filled with 36 holes. Next to the board there are three dishes, one contains screws (not used for this test), one contains cylindrical metal pins, and one contained small metal collars. The aim of the test is to use tweezers to place the pins into the board and place a collar on top, as shown in Figure 8.1. Each pin must contain a collar before moving onto the next pin placement. The score is the time taken to complete the task. Due to the number of conditions and tests in this study leading to time restraints, only half the board was filled (n=18). As with the Purdue pegboard test, the participants were told if they dropped any part, to not attempt to pick up the parts and obtain a new respective part from the dishes.

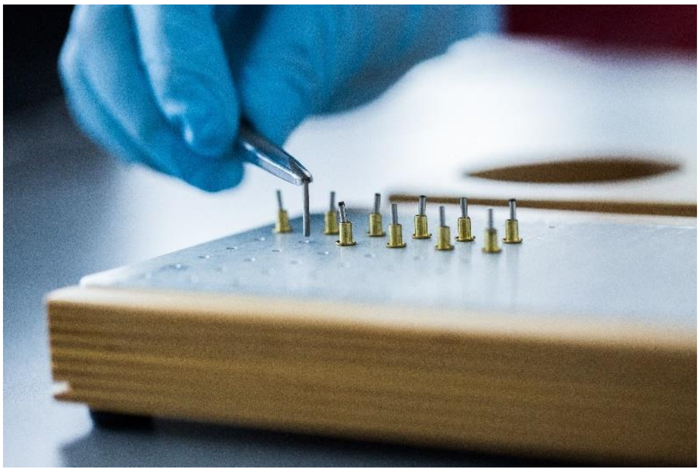


Figure 8.1. CSPDT pins and collar test.

Test familiarisation and learning behaviour

As in Chapter 6, the participants were made to practice the tests prior to the experiment being conducted. This was to circumvent any learning behaviour as the tests were conducted. These tests were carried out in the bare hand condition and were scored to establish a plateau in the results. A plateau was defined as three results in a row being similar (±2 pin/assembled parts for the Purdue test and ±3.0 seconds for the CSPDT), after a minimum number of 5 trials in each of the tests. In addition to this, to assess the possible effects of further learning behaviour throughout the dexterity tests, participants were asked to repeat one random condition to check for differences with their previous result. For example, once a participant had completed a test, they were then instructed to repeat the test in the same condition. The choice of which condition was re-tested was predetermined for each participant before the tests were conducted, and always fell near the end of the study (3rd or 4th test) as this is where learning behaviour is more likely to take effect. With the repeated test results, the first score was used in the data analysis if the results were different upon repetition.

8.3.4 Sensitivity measurement

The sensitivity test was chosen based on previous work conducted by Mylon *et al.* (88) who developed two simulated medical tactile tests (SMETT) to measure cutaneous sensibility. These tests have been discussed in Chapter 2 (see Section 2.6.1). Only the 'Bumps' SMETT test was selected for this study, as differences between gloves were more apparent in the study by Mylon *et al*. (88) with this test.

The bumps sensitivity test is composed of a flat elastomeric sheet with an attached guide, allowing for the finger to move down the columns, as shown in Figure 8.2a (14.0 × 14.0 × 0.8 cm). At random location across the sheet, 26 bumps have been manufactured onto the surface. The hemispherical bumps start at a height of 100 µm in size and increase by 20 µm up to 600 µm (Figure 8.2b). The participants were instructed to place their finger pads flat onto the surface, keeping the finger at around a 40° angle to the test bed, similar to the friction tests conducted previously in this thesis. This was to standardize the test and make the results more comparable between participants. If participants had applied their fingers so as to be aligned perpendicularly to the elastomeric sheet, the dispersion of mechanoreceptors activated is fewer than when the finger pad is horizontal to the board (264). In the previous study by Mylon *et al.* (88), the finger position varied between participants, making the results incomparable.

a) 

b)

	600		100		320	
540	260	360	280	400		220
580	500		160		560	120
	200	340		140		
		520	440		480	380
	180	240	460		300	
					420	

Figure 8.2. a) Bumps test bed developed by Mylon *et al.* (88) b) location and size of bumps (µm).

A light dusting of talcum powder was used, as in the original study (88). Efforts were made to avoid using this, to better understand the effect of gloves on tactile ability without a contaminant present. However, the contact induced too much friction and the fingers were found to slip in the gloves, and the polymer-polymer contact induced stick-slip friction. The talcum powder was spread as lightly as possible on the surface and practices were conducted to assess how light the dusting could be to reduce the friction. It was found that that a light dusting was sufficient. As this made some of the bumps visible on the surface, the participants were asked to close their eyes and their finger was guided by the researcher to the top of the plastic guide. Thus, the participants did not see the test bed in detail until after all tests were completed, to eliminate bias. Participants could explore each column at their own speed and were allowed run their finger up and down at their own leisure. All columns were used in each test and the columns were chosen in a forced randomized fashion before the study to further eliminate bias. In addition to this, the test bed was rotated 180° to increase the randomized possible orientations and prevent learning behavior for each test.

8.3.5 Mucin and application

Porcine gastric mucin (Type II, un-purified) was heated to physiological body temperature (37°C) via a water bath whilst in use. The mucin solution was the same as used in the previously in Chapter 7. To apply mucin to the gloves, participants dipped their gloved fingers into the solution (Figure 8.3). Unlike the application in Chapter 7, there the finger was dipped to the interphalangeal joint, in this study the fingers were dipped up to the knuckles to cover all the fingers. The fingers were held into the solution for 10 seconds. When removed, the mucin was rubbed over the palm and between the fingers using the dipped fingers of the same hand. This was to assess if the drying, crystallisation, or presence of mucin around the hand had an effect on performance. Excess mucin was shaken off until no drops fell from the glove, and then the test was conducted.

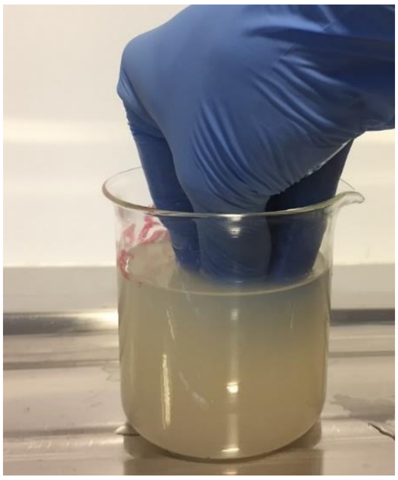


Figure 8.3. Application of mucin to the glove.

Mass transfer

As with the contaminants in Chapter 7, preliminary experiments were carried out to measure the weight of mucin transferred to the gloves by following the mucin application procedure. Participants were found to wear only medium and large gloves, thus only these sizes were measured. Two participants (both best-fit medium sized hands) donned five of each glove type and size (20 gloves in total). Mucin was applied using the procedure described. Gloves were then removed and weighed using a 5-point analytical balance (Analytical Sartorius, ±0.0001 g) to determine the amount of mucin transferred to the gloves.

8.3.6 Experimental procedure

All of the tests (Purdue pegboard, CSPDT and Bumps sensitivity) were performed in one 2 – 2.5-hour session with time for resting in between to avoid fatigue. Each of the dexterity tests were carried out in were carried out in 4 hand conditions: NRL, NRL + mucin, NBR and NBR + mucin. The sensitivity test encompassed the same conditions and a no-gloves condition. The order of tests conducted, and hand test conditions were conducted in a forced randomised fashion. This is a way of randomising test conditions, whereby permutations were checked and altered where applicable, to prevent certain conditions always being in a certain position. Participants were also not informed of the gloves being used, and packaging was removed prior to glove selection. However, due to the common colour variation between gloves, some participants were aware of which glove materials they were using. Tests were carried out at The University of Sheffield with a room temperature between 21.0-24.3°C. To eliminate the possibility of contamination, all of the equipment, with the exception of the gloves which were changed between tests, was cleaned with acetone and water between all tests.

8.3.7 Statistical analysis

Gloving conditions were compared to check for statistically significant differences within the raw data. Each set of data was checked for normal distribution using the Shapiro-Wilk Test for normality (192). The null hypothesis is that the mean result of each condition showed no difference between the two compared tests. Statistically significant differences are shown at $p<.05$. Where the null hypothesis of normality was not rejected within the data, statistical analysis was carried out using one-way analysis of variance (ANOVA) followed by a post-hoc Tukey's Honestly Significant Difference (HSD) where applicable (194). Where the dataset was rejected for normal distribution, the non-parametric Kruskal-Wallis test was conducted followed by a Dunn's Multiple Comparison test to assess where any significant difference occurs, if applicable (195).

8.4 Results

8.4.1 Mucin transfer

The weight of mucin determined to be on the gloves is shown in Figure 8.4. The medium sized NRL gloves averaged a deposit of 0.49 g (±0.026 g) of mucin, whereas larger gloves averaged 0.52 g (±0.056 g). Mucin on the medium NBR weighed, on average, 0.60 g (±0.067 g) whereas on the large, mucin weighed 0.62 g (±0.025 g).

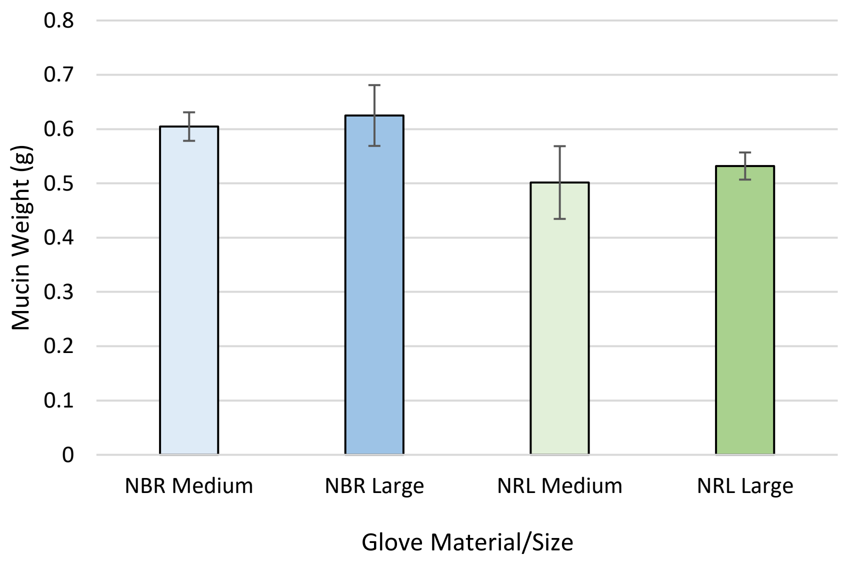


Figure 8.4. Mucin adherence to medium and large sized NRL and NBR glove. Error bars denote standard deviation.

8.4.2 FTIR

NBR

After the mucin application, there are slight changes in the NBR spectra compared to the washed glove, which are shown in Figure 8.5. The unwashed mucin sample has the absence of the C-O ester peaks at the 1050-1000cm^{-1} wavelength. The washed sample does have these peaks, but they are severely decreased in absorbance compared to the uncontaminated NBR gloves. This could be due to mucin being present on the surface. The increase in broadness and intensity of the peak from 3500-3100cm-^{1} indicates the presence of more hydroxyl groups (OH) on the NBR gloves. The overall absorbance of the uncontaminated NBR is dominant in the spectra, indicating that some of the mucin could still be present on the surface in the washed sample, reducing peak intensities. A higher intensity of peaks in the region from 900-400cm^{-1} is shown for the unwashed sample. This could be due to the mucin carbohydrates increasing the C-H intensities and the presence of disulphide bridges from the existing cystine links within the mucin (265). However, this is decreased after washing, indicating that washing has decreased some of the presence of the mucin (210). The peak shown at 2356-2332cm^{-1} shows the C-O bond of carbon dioxide, which has arisen because of an increase of CO_2 in the atmosphere around the sample, rather than the sample itself. These results show there are some changes to the surface of the NBR gloves when exposed to the mucin, which cannot be reversed with washing.

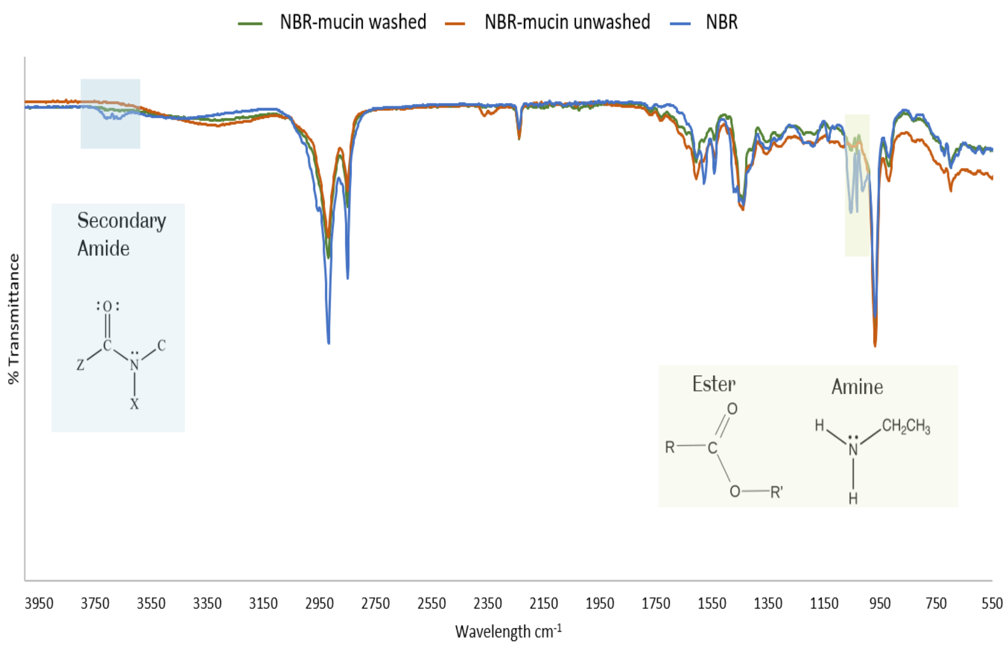


Figure 8.5. Spectra of NBR and mucin contamination.

NRL

The spectra for NRL when mucin is applied is shown in Figure 8.6. The unwashed sample has a peak at 1256 cm^{-1} which is absent from the washed sample. This is indicative of the carboxylic acid (COOH), which could arise from the terminus of the mucin proteins (265). Confirming mucin is likely to be on the gloves surface, as expected. There is also less absorbance of the main peaks in the unwashed samples, which indicates a reduction in the C-O/amine region between 1500-1300 cm^{-1} (210). There is very little difference between the clean sample and the washed sample. The slight reduction in absorbance could be due to the washing procedure or variation in the structure, as discussed regarding the AFM in Chapter 7. These absorbance shifts are minimal and are enough to indicate that the mucin has been removed from the surface of the NRL, showing very little and weak affinity of the mucin for the NRL material.

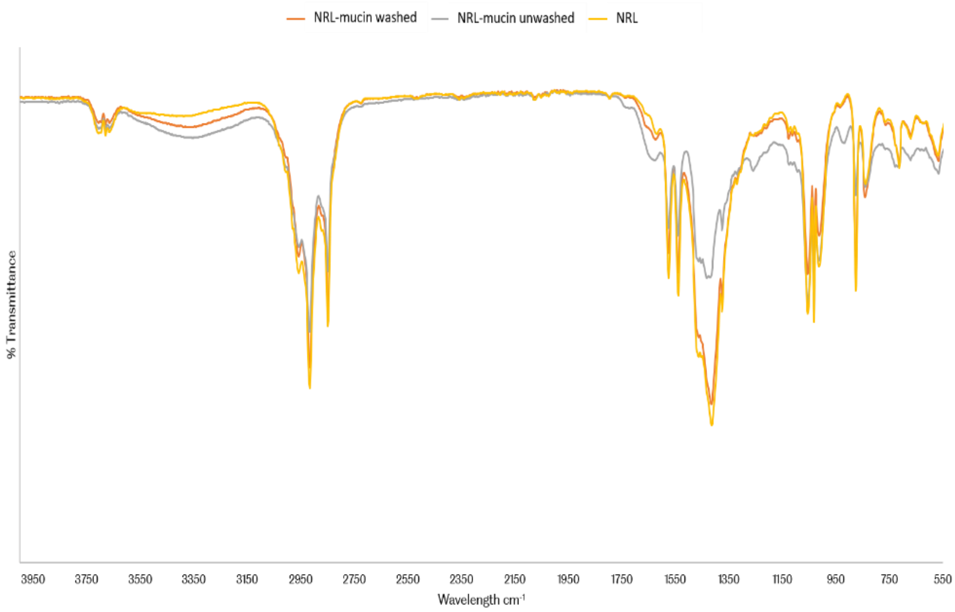


Figure 8.6. Spectra of NRL and mucin contamination.

8.4.3. Gross dexterity (Purdue pegboard test)

Left, Right and Both Hands (Combined Test)

The results of the combined Purdue pegboard test are shown in Figure 8.7. Data have been normalised against the dry glove condition (mucin contaminated time - dry glove time) to highlight the differences between gloving conditions and compare the impact of the mucin on the score. ANOVA tests were conducted, after the data were found to be normally distributed throughout the four conditions. The ANOVA shows statistically significant differences within the data (*F(3,66)=3.042, p=.009*). Tukey's HSD test results are shown in Table 8.1. NRL was shown to perform better, on average, than NBR with a score of 43 (±8) pins being placed, which is 1 greater than the NBR gloves (42 pins placed ±6). However, this was not significantly different (*H=1.400*, *p=.786*). When mucin was applied to the gloves, NBR was shown to have significant increase in dexterity, with the number of pins being placed averaging 46 (±6) (*H=4.209*, *p=.012*). This increase in performance was observed throughout all participants. On the other hand, with the NRL gloves, scores were lower than the dry condition with 43 pins being placed (±6). However, this was not significantly different from the dry performance (*H=1.400, p=.786*). The score was found to be 4 pins greater, than dry condition, with mucin contaminated NRL gloves in 2 participants. The remaining 13 participants were found to have lower performance scores with the contaminated NRL. Significant differences were found between the NBR and NRL when mucin is applied to both sets of gloves (*H=4.209*, *p=.013*).

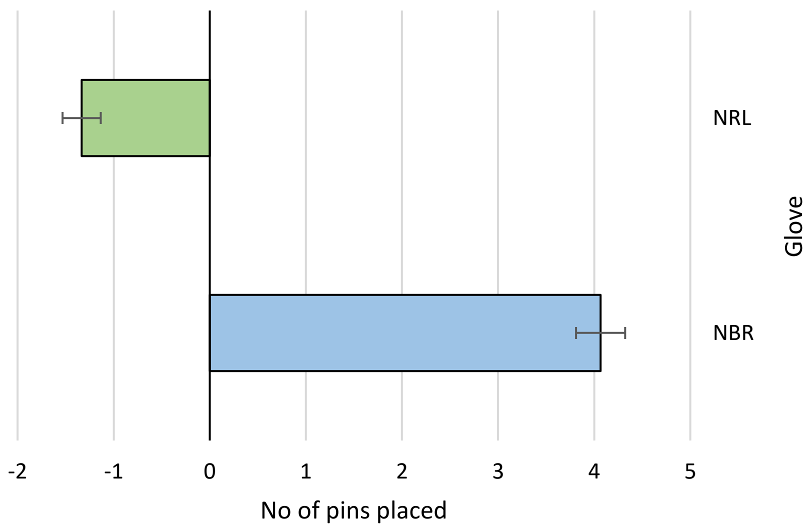


Figure 8.7. Normalised (mucin contaminated time - dry glove time) scores of combined Purdue Pegboard test. Error bars denote standard error.

Table 8.1. Tukey's (HSD) test results for the different gloving conditions in the Purdue pegboard combined hands result (ANOVA *F(3,66)=3.042*, *p=.009*).

Condition	**NBR + Mucin**	**NRL**	**NRL + Mucin**
NBR	*H=4.209 p=.012**	*H=1.400 p=.786*	*H=0.002 p=.900*
NBR + Mucin		*H=2.829 p=.179*	*H=4.209 p=.013**
NRL			*H=1.400 p=.786*

**Indicates statistical significance (p<.05)*

The number of dropped pins are displayed in Figure 8.8. The results show that the number of pins dropped when the NBR is contaminated, is no different from the uncontaminated (NBR= 0.60, NBR + mucin= 0.60). The same is observed in the NRL, however, more pins were dropped on average (NRL= 0.67; NRL + mucin= 0.67). Although the average number of pins dropped is higher in the NRL, only 9 pins were dropped in both sets of NBR gloves, and 10 were dropped in the NRL condition.

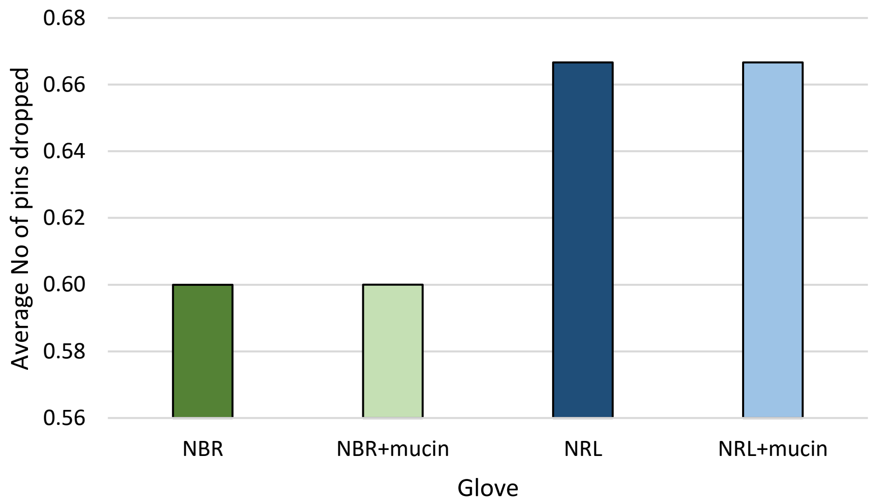


Figure 8.8. Average number of pins dropped across the gloving conditions in the combined test.

Assembly Test

The normalised (mucin contaminated time - dry glove time) results of the assembly segment of the Purdue pegboard test are displayed in Figure 8.9. The average number of parts assembled for the NBR (32.53 ±4.70) was found to be lower than the NRL (33.80 ±7.42). When contaminated with mucin, the gloves do exhibit differences in results. A decrease of 4.27 parts assembled is observed with the NRL gloves (average= 29.53 ±4.55). A decrease in the parts assembled were noted in all but one of the participants wearing contaminated NRL gloves. However, the number of parts assembled when the NBR glove was donned, increased by 1.60 (average= 34.13 ±3.85). This increase in score was observed in all participants. ANOVA tests show there is no statistically significant differences present between any of the data sets (*F(3,66)=1.838, p=.084*).

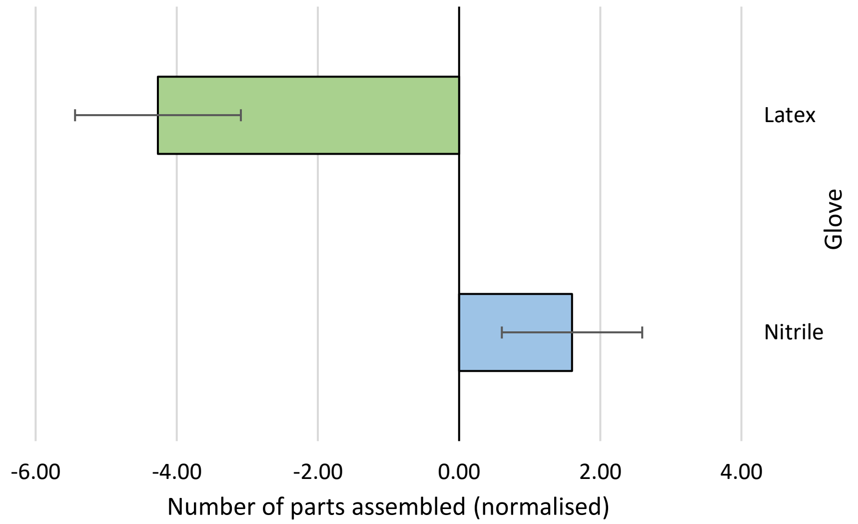


Figure 8.9. Normalised (mucin contaminated time - dry glove time) scores of assembly Purdue Pegboard test. Error bars denote standard error.

The number of parts dropped between the two conditions with each gloves also shows a difference, which is shown in Figure 8.10. When gloves are contaminated, both materials led to the dropping of 5 more parts than in the dry condition. In addition, more parts were dropped in this section of the test than previously (NBR=0.53; NRL; 0.67). More parts were dropped with the NRL gloves (10 pins, 0.87 average) than the NBR (8 pins, 0.67 average).

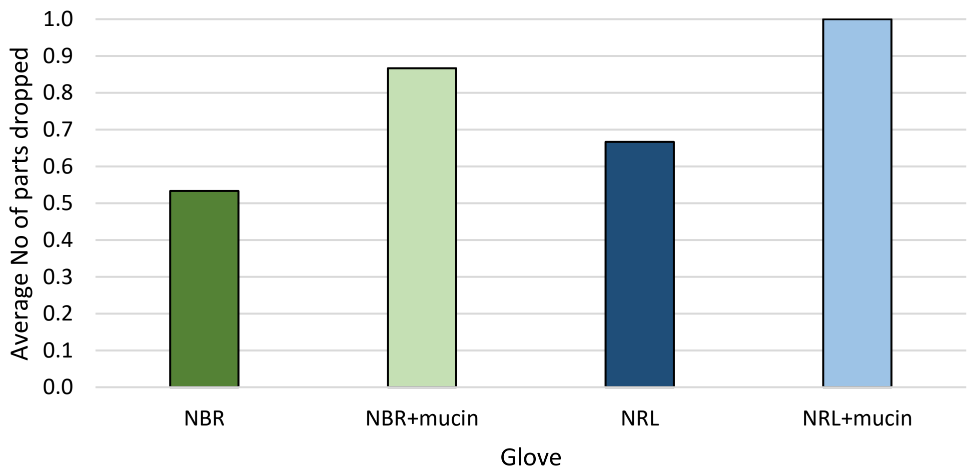


Figure 8.10. Average number of parts dropped across the gloving conditions in the assembly test.

8.4.4 Fine dexterity (CSPDT)

The results of the fine dexterity test (with pins and collar placement being completed with tweezers) show that when the NRL gloves were donned, the user performance was slightly quicker (1.83 ± 0.36 min) than the NBR (1.88 ± 0.34 min). However, the slight increase in speed is not significantly different (*Z=0.874*, *p=.382*). The normalised (mucin contaminated time - dry glove time) results for the CSPDT are shown in Figure 8.11. The results show that the performance with both gloves increased upon addition of mucin. When mucin was exposed to the NRL, the test was completed 3.6 (±16.8) s quicker than the dry condition. The increase in speed was noted in 12 of the participants, where three were found to take longer in the contaminated condition. When the NBR was contaminated, the test was performed 15 (±21.0) s quicker than the dry condition. All participants were shown to perform quicker when the mucin contaminated gloves were worn. All datasets were found to be non-normally distributed. Therefore, statistical analysis was carried out using the Kruskal-Wallis test. Statistically significant differences were found amongst the different conditions (*H(3)=9.754*, *p=.045*). Table 8.2 shows the results of the Dunn's post-hoc tests, which reveals significant differences to be between NBR conditions (dry and with mucin) (*Z=-2.652, p=.008*).

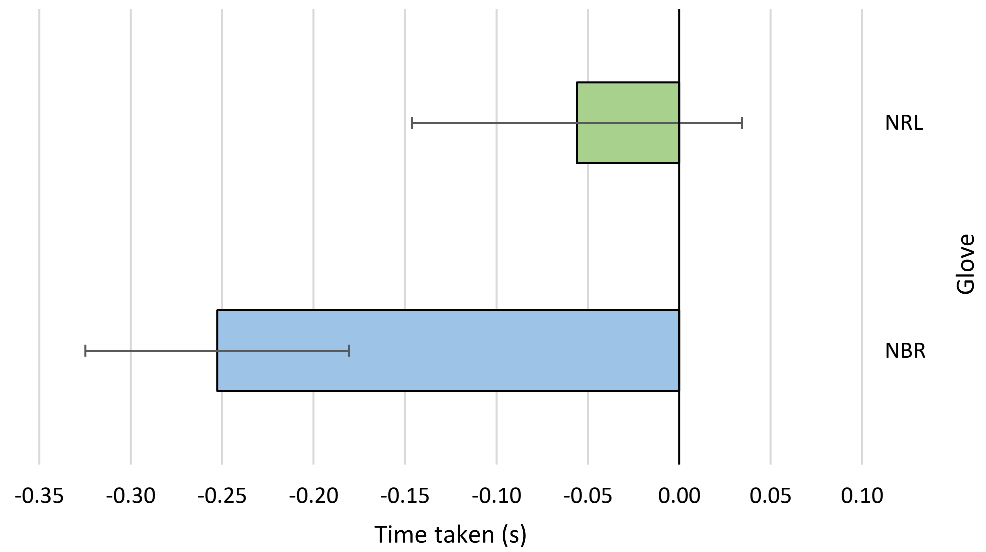


Figure 8.11. Normalised (mucin contaminated time - dry glove time) time from CSPDT test. Error bars denote standard error.

Table 8.2. Dunn's post-hoc test results for the different gloving conditions in the CSPDT results.

Condition	NBR + Mucin	NRL	NRL + Mucin
NBR	*Z=-2.652 P=.008**	*Z=0.874 p=.382*	*Z=-1.405 P=.160*
NBR + Mucin		*Z=-1.787 p=.074*	*Z=-1.256 p=.209*
NRL			*Z=0.532 p=.595*

**Indicates statistical significance (p<.05)*

Figure 8.12 shows the average number of pins dropped per test. On average, the participants dropped fewer pins in this test than the gross dexterity tests, with 4 pins being dropped in the NRL condition (average= 0.27), and 5 pins dropped in the NBR (average= 0.33). When mucin is added, there is a slight decrease with the NBR, with 4 pins being dropped in total (average 0.27). The NRL however, remains the same, with 4 pins being dropped across all participants (average= 0.27).

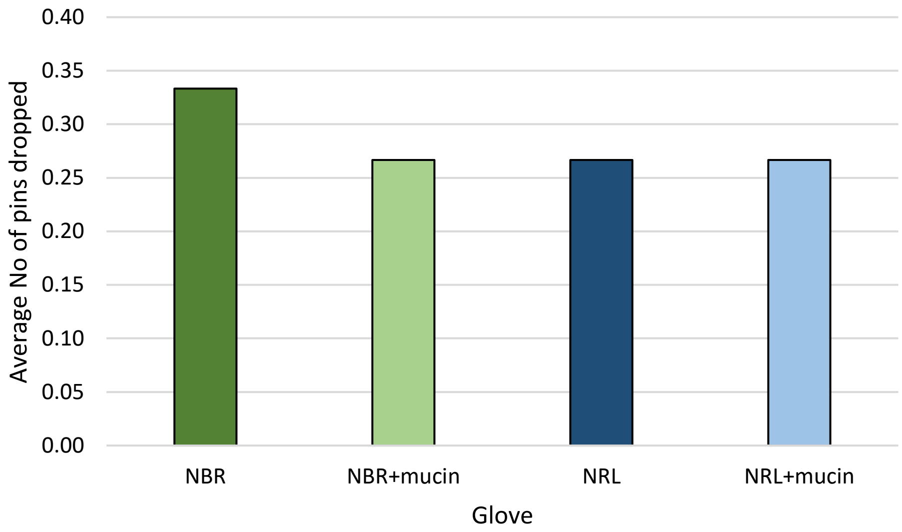


Figure 8.12. Average number of pins dropped across the gloving conditions in the CSPDT.

8.4.5 Sensitivity

One participant was only able to identify grooves running parallel between B and C as well as F (highlighted in Figure 8.13). These are not part of the test and presumed to be a fault in the manufacturing process. However, they were not mentioned in the previous experimentation by Mylon *et al.* (88). These grooves were noted by some of the other participants; however, they were also able to identify the bumps intended to be sensed. Another participant did not identify any bumps in any of the conditions, or without any gloves donned. Therefore, data for these two participants has been eliminated from the analysis (n=10).

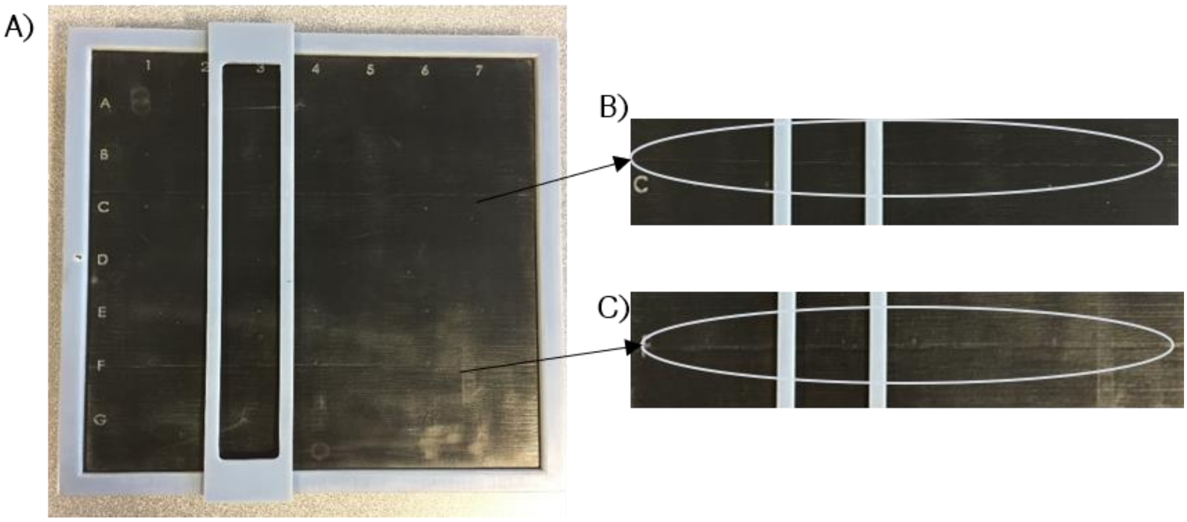


Figure 8.13 a-c. Grooves horizontal to the board. a) bumps test bed. b) groove running across between rows B and C, and c) groove running across row F.

Figure 8.14 shows the percentage of bumps detected in each gloving condition plotted for each bump size. All participants detected all of the bumps between 600 μm and 300 μm in the bare hand condition. When gloves were donned, this was shown to increase to 380 μm for the dry gloves. With the bare hand, participants felt bumps down to 180 μm, giving an average detection of all bumps at 75.2%. However, when gloves were donned, the LOD was shown to decrease. In the NBR gloves, the LOD 280 μm, when contaminated with mucin the LOD did not decrease, however 30% more participants were able to detect down to the 280 μm, rather than 10% in the dry condition. NRL had a greater rate of detection, with a LOD down to 220 μm. However, when mucin was applied, the detection rate decreased to 260 μm. Although the detection rate of the bumps is still better in the NRL, the mucin has been shown to increase detection of the bumps in the NBR.

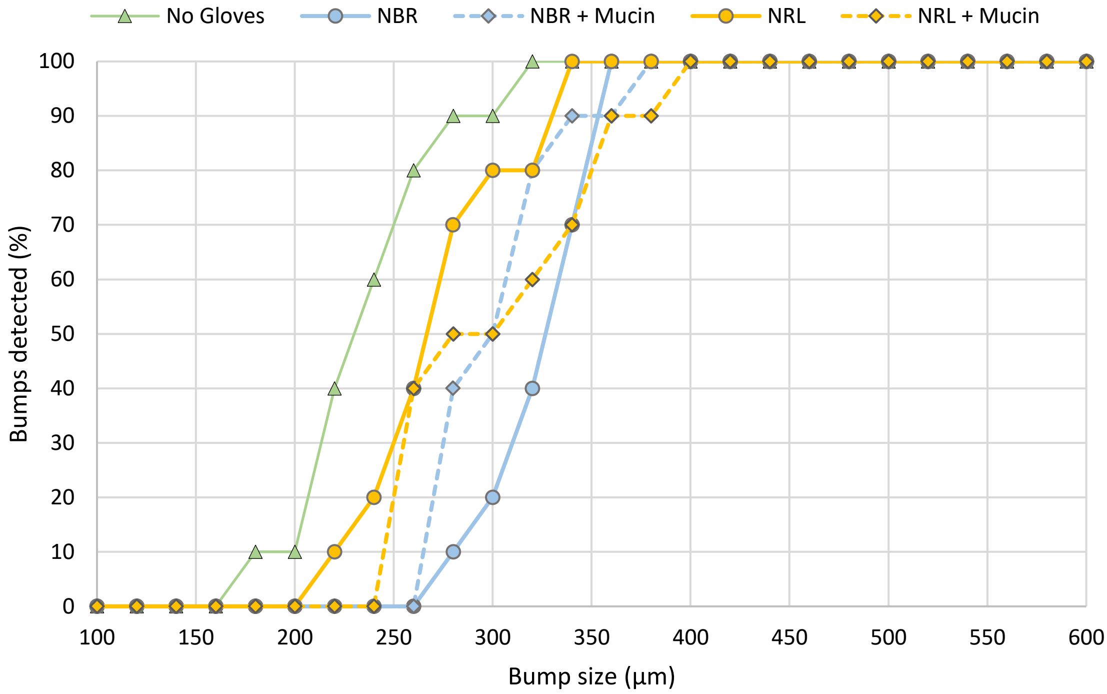


Figure 8.14. Results of bumps sensitivity test showing the percentage (%) detection rates at each bump size.

8.5 Discussion

8.5.1 Binding of mucin

The spectra of the FTIR confirms the previous tests regarding the binding and affinity of the mucin for the NBR glove, and less attraction to the NRL. The mucin was easily washed off of the NRL, but changes remained on the surface of the NBR after washing. That is not to say that mucin is still present on the surface of the NBR after washing, as the changes in the spectra could be down to other factors, one of which could be due to the leaching of phthalates out of the gloves. It is documented that the microstructures of polymers change with exposure to water due to phthalate leaching (207, 266). However, this process tends to occur over a longer period than used in this study. There are several other additives that contribute to the observed spectra, such as the stabilisers, dyes, antioxidants, and treatment methods. It is possible that some of these additives could have reacted with the mucin in this study, resulting in the observed spectral changes. NBR and NRL both degrade by oxidative chain scission, a process whereby oxygen will break the C=C bonds to become C=O, breaking the polymer chain (267, 268). Occurrence of a C=O band does occur at stronger absorbances with NRL and mucin, but not in the NBR and mucin, leading to the inference that there may be differences in the changes with the microstructure of the mucin itself when on the gloves. Differences could arise due to changes in orientation of polymer chains, degree of crosslinking and degree of crystallisation of the mucin, as discussed in Chapter 6 (269). In order to understand the changes on the surface, confirmatory chemical analyses could be used to explore that. However that was considered to be beyond the scope of this work. It is clear that the mucin has a stronger attraction to the NBR material, as it causes changes in the surface chemistry of the glove, has a larger estimated film thickness and greater contact angles than the NRL material.

8.5.2 Effects of mucin on dexterity

In Chapter 6, it was shown that the stiffer gloves had a greater detriment to dexterity. Therefore, it was thought that, as the mucin dried, the gloves may feel stiffer due to the evaporation, and the differences in this perception may affect performance. As no other studies have been found assessing how contamination affects the dexterity performance of gloves, is it not clear what is occurring to improve dexterity with NBR, but not with NRL in the pegboard test. The assembly test proved to be more difficult when the mucin was present on both gloves, and participants noted more difficulty in their ability to carry out the task when using NRL. Where lubricated, a greater level of fatigue can be induced through increased, and prolonged, gripping. The drying and stiffening of the mucin protein may occur over a prolonged period, especially with more tasks and a variety of movements seen in the medical profession. However, it does not appear to be the case in this study, or with this particular contaminant. It is most likely the increase in dexterity is a result of a more 'optimum' friction, and ability to feel. If pins and parts are easier to grab and place, as is the case with NBR and mucin, performance will be quicker.

External stimuli and temperature

When gloves are contaminated with proteins, such as mucus, there is a greater risk of dexterity changes due to changes in feel and possible micro changes in the surface structure, as shown in the FTIR results. Perception of performance is also known to have an effect on dexterity (270). It has been shown in previous studies that performances are affected by an environmental stimulus. A review by Heus, Daanen, and Havenith (271) showed that both gross and fine finger dexterity is significantly reduced when the psychological effects of the cold are exerted onto the human body. More specifically when assessing effects of external stimuli on or around the hands, Maley, Minett, Bach, *et al.* (272) found that performance with the Purdue pegboard was significantly decreased when the arms of the participants were cooled to 10°C. However, Ray, Sanli, Brown, *et al.* (273) found little difference between dry hands and hands when wet or cold after completing the pegboard test. However, the study does show a decrease in performance when the hands are both wet and cold. It is possible these studies are measuring the effects of muscles constricting to preserve warmth. In this study, warming of the hands (through the heated mucin) may have improved gross dexterity with the NBR but decreased gross dexterity with the NRL gloves. An increase in dexterity as a function of increase in temperature has been shown previously by Chen, shih, and Chi (262), who showed a strong correlation between warm hands and an improved performance with the Purdue pegboard. As the gloves move, the protein will cool down over time, which will induce evaporation and different sensations on the hands. The cooling effect could be perceived differently through the materials, brought about by distinct interactions of the mucin with the glove, specific hand movements, film thicknesses, and heat transfer. It is possible the dexterity of the NRL was affected by the cooling action as the mucin was repelled, however the temperature was not checked over the course of the study. Much of the work conducted looking at the effects of external stimuli are centred around lighting and temperature, rather than something pressing against the hand or the sensations as something being exposed to the hands/evaporated.

Protein conformational changes

The mucin would have changed in viscosity due to the movement and differences in pressure being applied (235, 274), which would affect how the mucin feels when pins are being grabbed (i.e. a thicker formed mucoadhesive gel will change instinctive applied force, than a watery solution). Furthermore, the movements and airflow around the protein can cause differences in mucin interaction as well as the physical properties of the gloves. As the gloves move, the already decreasing temperature will be rapidly decreased further. Ligtenberg, Meuffels, and Veerman (275) shows that at a lower temperature the flow rate of saliva decreases, due to mucin aggregation and changes in protein conformation. Again, this would have an effect on the perception when participants grab the pins in the Pegboard test, and when holding the tweezers in the CSPDT. The results of dexterity tests, where changes are occurring over the course of the test, need to incorporate the psychological aspects of the perception of the task. It is proposed that as the NRL is generally tighter fitting to the hand, as observed in previous chapters (Chapters 4, 6 and 7), the cooling effects as well as the changes in protein viscosity and conformation have a greater effect on the participants. This could be the reason for the increase in dexterity with the CSPDT, because of the more static position, the participants may not be feeling and responding to the changes over time.

The changes in conformation of the protein may also be a reason for performance decrease in both gloves with the assembly tests. Excess mucin dropping off of the gloves into the washers appeared to be the greatest hurdle, as the washers stuck together and required separation. The mucin in this position would also pull the positively charged metal to the mucin, making separation of these washers slightly more difficult. This was more frequent in the NRL gloves, over the NBR, as more mucin ran off of the NRL gloves due to less mucin-glove interaction.

8.5.3 Friction and film formation

Purdue Pegboard

Where mucin was present, it was noticed when participants had NBR gloves donned, users had difficulty trying to grab washers from the concave dishes. However, the difficulty was apparent when trying to grab all components when NRL was donned. The frictional properties of both the NRL and NBR gloves are shown in Figures 8.15 (a-b). These are taken from the friction obtained in Chapter 7 (see Section 7.4.3), assessing friction with tool 7 (smooth steel), which is replicable of the surface of the pegboard pins, as discussed in Chapter 6. The CoFs decrease on average by around 0.19-0.28, across all loads, when mucin is applied to the NBR glove. When mucin is applied to NRL gloves, the friction decrease is greater. At the 1 N target load, the CoF decreased by 1.18, which then reduces to between 0.84 and 0.89 across the loads. However, it does not appear that the mucin affected the frictional properties to the extent that many more pins were being dropped. Further work could be conducted to measure the loads used to grab the pins, in addition to further assessments of the dropping frequencies, in order to evaluate how the mucin may affect grip. It may be that the participants were likely experiencing difficulties in adjusting the grip to accommodate the changes in frictional properties. Thus, participants could have been taking longer to pick up the pins when the gloves are contaminated with the mucin. The higher affinity of mucin for the NBR gloves is aiding optimal friction and adhesion, allowing pins to be picked up more easily in the Purdue pegboard test. The protein conforming under a higher load over time as the water is pushed aside appears to decrease the friction in the NRL.

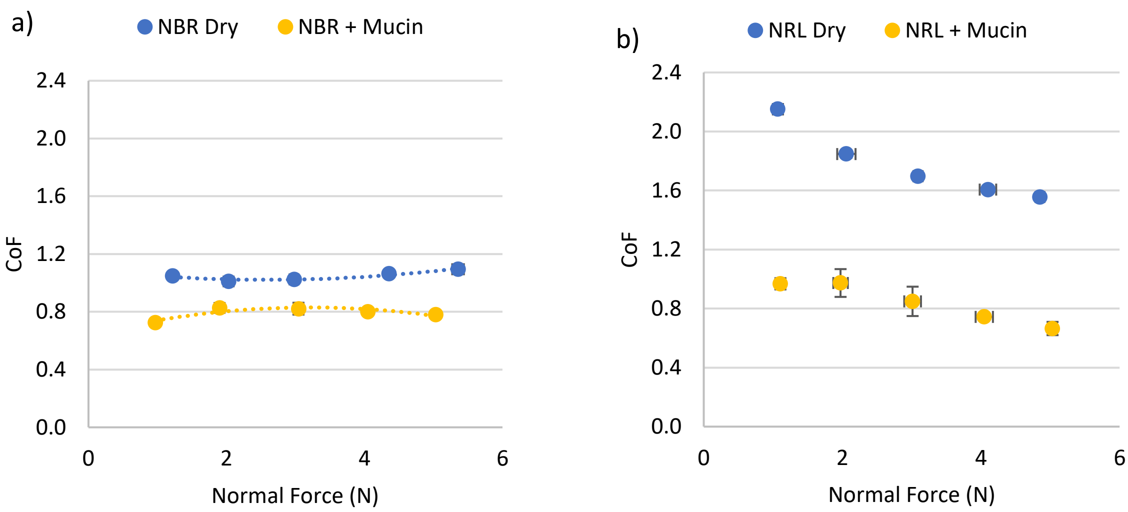


Figure 8.15 (a-b). CoF of a) NBR and NBR with mucin; b) NRL and NRL with mucin on smooth steel across a 1-5 N target load range (as tested in Chapter 7). Error bars show standard deviation.

CSPDT

When assessing fine dexterity in the CSPDT, it is shown that when mucin is present, there is an increase in dexterity with both glove materials. The NBR is shown to allow a much greater dexterity than the NRL when contaminated with mucin. It would appear in the fine dexterity, addition of the mucin causes an 'optimum' friction, due to the formation of a mucoadhesive film. This is aided by the static positioning of the thumb and proximal index finger skin/index finger pad, which would contain some mucin between the metal and the gloves. Under shear stress, this film formation prevents microslips through an increased adhesion (233, 250). However, the friction coefficient of the gloves when mucin is applied, is shown to be lower in Figure 8.16(a-b), which is reproduced from the results in Chapter 7 (see Section 7.3). It must be considered that the friction test was unlike the conditions used in the CSPDT, where the average elapsed time was around 3.5 minutes and there was some movement of the hand. In the friction tests the finger pad was placed onto tweezers and moved down after holding for a few seconds. Thus, it is unlikely a tribofilm had developed during the friction tests.

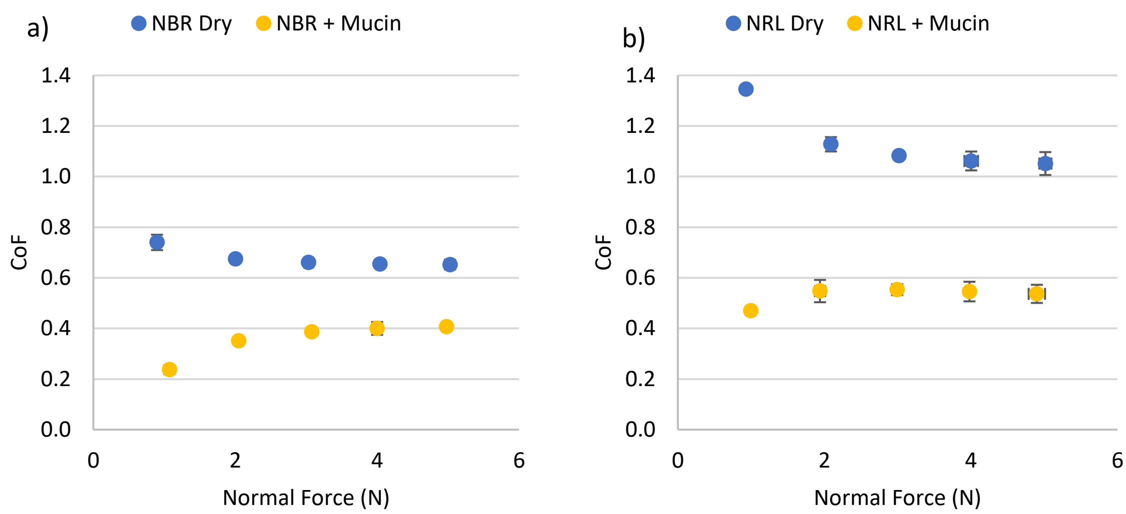


Figure 8.16 (a-b). CoF of a) NBR and NBR with mucin; b) NRL and NRL with mucin on tweezers (tool 5) across a 1-5 N target load range. Error bars show standard deviation.

Thus, it is hypothesised that there is more affinity of mucin for both the NBR gloves and the metal, which is aiding friction by bringing the surfaces closer together, allowing pins to be picked up more easily in the Purdue Pegboard test. This allows for greater precision when completing the tasks. When applied to NRL, the mucin has less affinity for the surface and may be acting as a lubricant in the first instance, making the surfaces more slippery and harder to grip. However, over time, the movement and change in force when grabbing pins/tweezers aided the thinning of the mucin viscosity, which would have contributed to changes in the mucin. The muco-adhesive film takes time to form and is not instantly apparent, as these tests were 30 seconds/1 minute, there may have not been enough time to allow development of this film. This hypothesis is also supported by the results of the CSPDT which shows that mucin improved dexterity to participants when wearing both glove materials. The static positioning of the finger and thumb used to hold the tweezers has allowed the formation of a thin muco-adhesive film, negating any microslips between the gloves and the metal. In conjunction with this, the tweezers had textured grooves on the surface to enhance grip. The mucin could have flowed into these and increased the contact area with the gloves, further increasing friction.

8.5.4 Effects of mucin on sensitivity

Mylon *et al.* (88) observed that NBR had a higher detection rate than NRL when compared to the bare hand, whereas this study presents an opposite result. The difference in participant number (32 V.S 10) could be a reason for this difference. However, in the previous study by Mylon *et al.* (88) the thickness of the NBR gloves was less than that of the NRL (NRL= 0.123 mm, NBR= 0.074 mm). Thus, it could be argued that a better comparison can be drawn from this study, due to the gloves being of similar a thickness. Another reason could be the standardisation of finger orientation used in this test. In the previous study, participants were not instructed on how to place their fingers onto the test bed. Having the fingers flat would induce more accurate results through an increase in surface contact area, and participants are more inclined to feel the bumps through increased contact area and mechanoreceptor activation (276). When the gloves are dry, the gloves will deform to the bumps, increasing the likelihood of mechanoreceptors picking up the change in stimuli (264). In addition, the material stiffness may hinder the detection of the bumps. When the gloves are moving over the bump, there will be some minor pulling of the glove as it deforms, shown in Figure 8.17. In the stiffer NBR material, this effect will be lessened as the material is stiffer and will deform less (277). This has been explored and discussed in terms of asperity contact in Chapter 6.

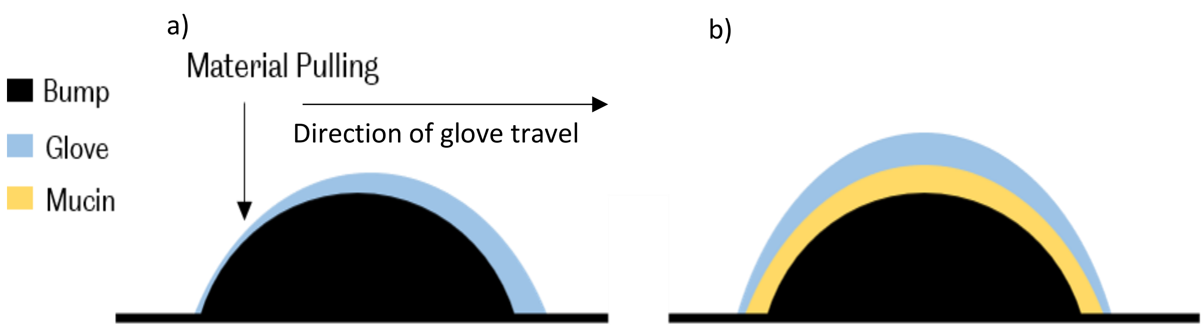


Figure 8.17 (a-b). a) Materials pulling when deformed to elicit tactile sensation b) mucin allowing the material to glide over the bump.

When mucin contaminates the NBR gloves, the affinity of the mucin for the glove will cause some tack as the mucin competes for interaction with the nylon and the gloves. This increases some adhesion of the mucin to the bumps over time, improving detection rate of the bumps. However, the mucin did not allow for better sensitivity beyond the limit of detection of the dry gloves in the NBR – both conditions had a detection limit of 280 µm. When mucin is present on the NRL gloves, only weak interactions hold the substance to the surface. Therefore, when in contact with the test bed, the mucin will run off the NRL and cause flooding around the bumps. This separates the two surfaces, causing a decrease in detection, as seen in Figure 8.17. However, it is possible there is also development of a tribofilm, as seen with the metal pins. As the finger is run down the test bed, the mucin will change due to motion, pressure, and temperature changes. It is possible that due to the interaction with the NRL, the mucin is pushed out at the start of the test, but as the finger runs down the column, less mucin is present. Also, the participants ran their fingers from side-side and up and down to determine the bumps. As this movement occurs the mucin will experience shear thinning (278). This has the potential to increase the rate of tribofilm development, due to less solution presence and more water evaporation, as in Figure 8.18. This could also be the reason for a loss of detection when mucin is added to the NRL, as many of the smaller bumps felt by participants, when wearing the dry NRL are at the top half of the board. In the NBR, the low tack film will be established earlier as the mucin binds to the gloves, causing some possible stick-slip with the bumps, enhancing the detection rate.

Bump test column	Mucin quantity
Finger placed on board at the top	Maximum mucin quantity as finger is placed onto the board. Finger floods the bumps = less detection of smaller bumps
	Mucin running off of the fingers and glove is brought closer to the surface
	Less mucin contained by the finger
Finger reaches the bottom	Little to no mucin on the bottom row. Film development more likely

Direction of finger travel

Figure 8.18. Representation of the mucin quantity of NRL on the bumps test board.

8.5.5 Significance of findings

A summary table (Table 8.3) is provided to show the implications of contaminating gloves, and their effects on performance.

Table 8.3. Performance of mucin contaminated glove performance when compared to the dry condition.

	Glove material	
Test	**NBR**	**NRL**
Gross dexterity	Increase	Decrease
Fine dexterity	Increase	Increase
Sensitivity	Increase	Decrease

In Chapter 7 it was shown that contaminants, such as mucin, affected the frictional properties of the gloves. This was expected, due to the addition of a substance that would act to serve as a lubricant, lowering friction. This chapter has further shown the implications of that change in friction. By lowering friction vastly, as observed with the NRL gloves, the detriment to gross dexterity is apparent. In addition, the contaminated gloves are shown to decrease the sensitivity in NRL gloves, which may lead to sensitivity issues, which could lead to missed lumps, small lacerations, and damage to the skin (13). The impact of the contaminants on the NBR gloves, however, are shown to be beneficial, increasing dexterity and sensitivity, in this case. This would suggest that, of the two most common materials, the NBR material is a better selection for glove users, particularly in the medical field. However, this must be interpreted with some caution. Whilst the NBR shows an improvement over the dry condition, and the NRL, in this work, it has only been conducted on one type of NBR glove. It may be the case that gloves which have been subjected to a different surface finishing (such as silica dipping), will have a different surface chemistry, and therefore a different chemical reaction to the contamination.

8.6 Conclusions

The findings of this chapter are as follows:

- The mucin contaminant has been shown to affect both the performance measures of sensitivity and dexterity. Through different interactions, the results exhibited are different between the materials.

- Mucin has a greater affinity for the NBR gloves due to the polarity, leading to mucin-NBR interaction. On the other hand, the NRL gloves will repel the mucin through hydrophobic mechanisms and exhibit less interaction.
- When contaminated, the NRL gloves show a severe reduction in friction and a decreased gross dexterity and sensitivity. NBR on the other hand, shows a smaller, but significant, decrease in friction but an increase in performance. The development of the protein film, however, has aided performance in the CSPDT by the way of adhesion, circumventing any micro-slips between the glove and the tweezers, improving dexterity with both glove materials.
- The chapter has overall shown that contaminants affect performance when medical examination gloves are worn. If the contaminants are decreasing performance, as seen in the NRL, then the effects could be potentially detrimental to the medical practice. On the other hand, if there is an improvement, then understanding how the gloves are improved, and with what particular glove films, could aid the market targeting of gloves for specific use.

Chapter Nine: Blood friction and synthetic development

In Chapter 7, it was shown that contaminants have a varied affinity, and reaction, to the different glove materials. However, in Chapter 3, the respondents to the questionnaire demonstrated that blood is the most frequent contaminant to contact the gloves, at least in a medical setting. This was not used as a contaminant in the previous chapter due to the availability and shelf life of blood. Therefore, this chapter will explore the use of blood in assessing how the friction of medical examination gloves can be modified upon exposure (232). This chapter closely relates to the frictional tasks carried out in Chapter 7. As blood is the most commonly contacted biological fluid, as discovered in the questionnaire in Chapter 3, assessing frictional modifications of gloves is important for understanding the conditions gloves are used in (6). To circumvent the storage and ethical issues there is a need for a synthetic blood for use in future studies, in order to allow this to be replicable in industrial settings. Thus, this chapter of the thesis focuses on the development of a representative synthetic blood which may be used in industry to assess friction modification.

9.1 Introduction

Blood characterisation

Blood is a liquid connective tissue which is comprised of red blood cells (erythrocytes), white blood cells (leukocytes), fragmented cells known as blood platelets (thrombocytes), and an extracellular matrix, which is often referred to as plasma (279). The plasma is composed mostly of water, which helps with the suspension of ions, proteins, and nutrients in the blood matrix. Blood tissue which contains all of the plasma and cell components is known as 'whole blood' (280). The viscosity of whole blood is found to be between the range of 1.38 and 5.84 mPa-s at 37°C (281–285), with most of those studies placing the viscosity in the 3-4 mPa-s range. However, most of these studies mixed anticoagulants into the blood, most commonly ethylenediamine tetraacetic acid (EDTA) to prevent clotting. Although only a small amount is added (around 2µl per ml), there is a change in the way the blood behaves and reacts. This is because EDTA works by chelating (removing) the calcium ions to prevent any cross-binding in the blood, which prevents clotting. Mayer and Kiss (285) have shown that anticoagulants added to the blood do give a small change in the viscosity. Blood was measured at a viscosity of 3.54 mPa-s at 37˚c, which, on average, dropped to 3.40 mPa-s when EDTA was added. Reuf, Gehm, Gehm, *et al.* (284) made similar findings to this. Citrate can also be added instead of EDTA, however, this does not bind as strongly to the calcium-blood complex as EDTA, thus can be reversed with the addition of calcium. This is a much more complex method, as the citrate needs to be added at the correct concentration and volume in order to prevent coagulation (286). Several studies have also reported variations in the density of whole blood. Vitello, Ripper, Fettiplace, *et al.* (287) states the density of blood is measured to be around 1043-1060 kg/m^3. Whereas Benson (288) states the density is between 1025 and 1125kg/m^3. Most of the published studies place the density of whole blood between 1025 and 1060 kg/m^3 (287, 289–293).

Synthetic bloods

To better study how fluids, such as blood, affect glove material performance there is a requirement for the development of a synthetic blood. This is to avoid the issues with storage and ethical queries regarding using blood in research practice. Much of the research around synthetic bloods created in the literature are based on matching the viscosity of whole blood. Where studies using bloods are published, they use whole bovine, porcine, ovine, or equine blood (294). This is because the physical properties of the animal blood are similar to those of whole human blood. In order to assess the effect of blood on glove performance whole blood is required, as this is the blood which is most likely to be contacted. Blood which has been separated into cells and plasma could also contaminate gloves, such as that in a medical laboratory setting. Although, in more emergency clinical applications, whole blood is most likely present. The likelihood of developing a fluid that acts exactly like whole blood in terms of behaviour out of the body and chemical reactivity is low, due to the variety of biological compounds constructing the tissue. Existing synthetic bloods are separated into two areas; one of which is the medical use, focusing on the ability of oxygen to readily bind and unbind as required (280). The second is for scientific study, mostly concerning forensics, such as blood spatter and use for medical research regarding equipment and flow (295). These materials are developed to mimic a specific characteristic of blood, primarily viscosity, none of which look at the frictional properties or interactions with medical gloves.

9.2 Aim and Objectives

There are two aims to this chapter. The first aim is to identify if the presence of blood affects the frictional properties of NBR and NRL gloves. This allows for a fundamental understanding how blood interacts with the different glove materials, allowing an assessment of how friction is modified, much like in Chapter 7. A previous study looking at the friction of medical gloves with blood (116) did not state the nature of the blood which was used, nor whether the blood had been treated (e.g. whole blood, fresh, or any if any anti-coagulants were present). In an ideal setting, the blood would be drawn fresh, just before the frictional analysis is conducted. However, to get fresh whole blood, without an anti-coagulant is difficult due to the rapid coagulative nature of the blood (296, 297). To circumvent this coagulation, as mentioned, anticoagulants are normally used.

The second aim of this study is to develop a synthetic blood which may be used for future studies regarding friction. As blood is contacted in various stages of the drying properties (fresh, gelled, and dried) there are challenges with mimicking the properties of these. This work will focus on creating a synthetic blood which is fresh (i.e. still wet without drying). In a medical situation, this will be more representative of the blood exposed to during minor medical procedures. A variation of sugars, stabilisers and proteins, which have been used previously to make bloods of varying viscosities (295), and are easily obtainable and require little storage issues, were selected. Comparisons will be drawn between the friction coefficients of the blood and the friction obtained from the synthetics in order to assess if blood can be removed from future studies of this ilk. By removing the tissue, this allows industries to assess frictional behaviour modification of a common contaminant, without the need for safe storage, considerations for shelf life and ethics, or concerns around disposal of materials.

9.3 Materials and methodology

Ethical approval was received by the Research Ethics Committee of the Department of Mechanical Engineering, University of Sheffield (No 022733 and 022735).

9.3.1. Glove Materials

The NRL gloves were branded ‘Safetouch’ and the NBR gloves were provided by Synthomer. These materials were the same as those used in Chapter 7 and 8, regarding contaminated glove friction and effects on user performance.

9.3.2 Blood

Whole ovine blood was used with a citrate anti-coagulant added for this study. The blood used was also compared to that of the fresh, whole human blood for contact angle analysis and FTIR. This was to assess whether the initial behaviour and interaction with the different materials is the same between the two tissues. If the behaviour is shown to be similar, this would give the further validation to using a blood which has anti-coagulants present for future tests.

Whole blood

For the whole blood comparison, blood was drawn from the finger of one participant, (male, 28) using an Abbott lancet kit, as seen in Figure 9.1(a). This kit consists of a spring-loaded lancet device (10 × 1.2 cm) which is loaded with a lancet needle (0.3 cm). This is placed over the fingertips and the button forces the lancet to pierce the skin to the depth of a few mm, drawing blood, as shown in Figure 9.1 (b).

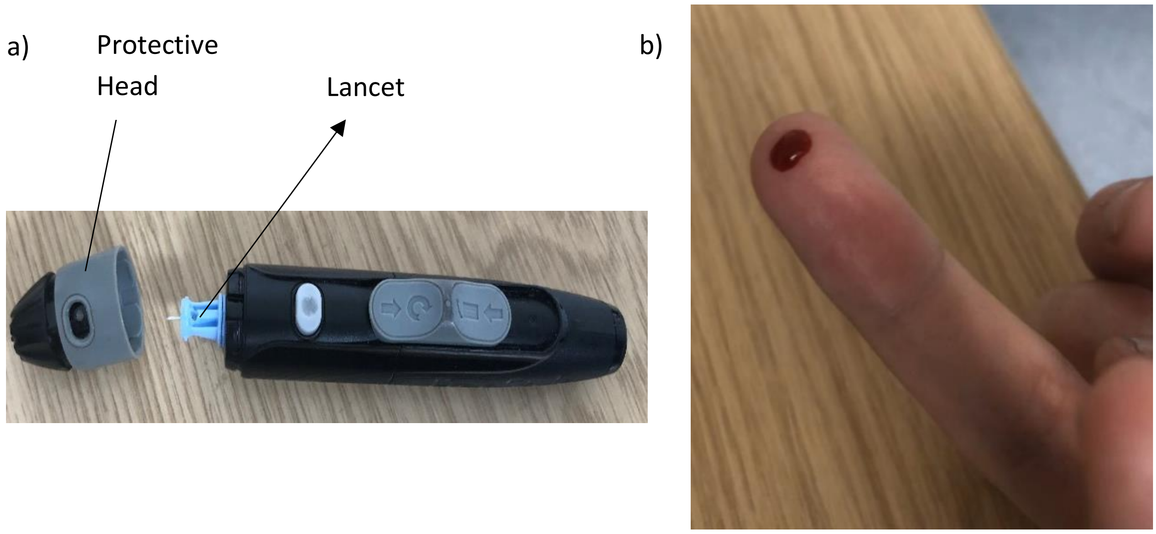


Figure 9.1 (a-b). a) Lancing device with protective head detached to reveal the lancet; b) blood drawn from finger after pricking with the lancet device.

Ovine blood

Whole ovine blood was purchased commercially, with a sodium citrate anticoagulant added. This was stored in the fridge when not in use as to prevent warming. When in use, the blood was heated to 36-37°C in a water bath to get to physiological temperature, which is the temperature in which fresh blood is most likely to come into contact with the gloves.

9.3.3 Synthetic blood development

Solutions were made up using methods from previously published literature looking at viscosity and flow (295). For industry, the materials used in this study are easy to obtain, with little concern regarding storage. There are many variations of synthetic bloods in the literature and available to purchase commercially, however by creating variations of blood materials already tested for viscosity, the study can easily assess which synthetic solution gives similar friction properties to that of real whole blood. Slight variations have been made to those proposed by Millington (295) based on availability of materials, viscosity of materials, and use of stabilising solutions to prevent mould growth over time. Some of the constituents were used which have a similar nature to the chemicals used by Millington (295), and the volumes adjusted accordingly. Synthetic blood solutions (SB) were created consisting of variations of:

- Glucose syrup (Lyons)
- Glucose anhydride (α-D-Glucose, Boots)
- Glycerol (100%, Value Health)

- Flour (plain, BeeRo)
- Methyl cellulose (Sigma Aldrich)
- Porcine gastric mucin (Sigma-Aldrich, Type II, unpurified)
- Sodium chloride (Sigma-Aldrich)

All materials were purchased commercially. Red food colouring was also added to the solutions for aesthetic reasons, as well as adding colour to visually see the solutions on the gloves, as many were colourless. The solutions were made up in accordance with the differences in their properties (some solutions contained more agents which thickened the solutions or made them waterier). The solutions were mixed together into a beaker, poured into sealed containers, and stored at room temperature in a dark and dry area. A total of 7 solutions were developed, via mixing the ingredients shown in Table 9.1. Solutions 1-3 were made in the first instance, with the proceeding solutions being created based on the observations made from the initial material characteristic testing.

Table 9.1. Constituents of the SB solutions

	Solution						
Ingredient	**SB1**	**SB2**	**SB3**	**SB4**	**SB5**	**SB6**	**SB7**
Glucose syrup (g)	2.25		3.75	0.25	2.25	½ of SB1	¼ of SB1
Methyl cellulose (g)	1.25				0.2		
Sodium chloride (g)	0.25		0.25	0.25	0.25		
Glycerol (ml)	1.5			0.25	1		
Plain flour (g)		7.85		3.75			
Glucose anhydride (g)		1			1.4		
Porcine gastric mucin (Type II) (g)		0.15					
DI water (ml)	44.5	30	20	44	20	40	40
Food colouring (ml)	0.5	4	0.5	2	2		

9.3.4 Properties of blood and synthetics

Density

The density of the SB solutions, and the ovine blood, were calculated using the method described in Chapter 7 (Section 7.3.5). Density was measured by weighing 1 ml of each solution (Analytical Sartorius, ±0.0001 g). The density was then determined using equation 7.2. This test was repeated three times for each of the solutions.

Viscosity

To measure the viscosity of the SB solutions and the ovine blood, 10 ml of each solution was measured with a vibro-viscometer (*AND*, SV-1A, ±0.01 mPa-s.), discussed in Chapter 7 (see Section 7.3.2). Each solution was measured three times to obtain an average viscosity. Each sample was shaken for one minute, before filling the sample well, to disperse colloidal suspensions and induce homogeneity.

pH measurement

The pH of the developed SB was monitored using HANNA benchtop pH meter (HI-2211, ±0.01 pH). The glass probe was inserted into each solution and left to reach a pH balance reading, which was then recorded. This test was conducted only once due to the high sensitivity and availability of the equipment.

9.3.5 Contact angles

Contact angles were measured to compare the surface interaction of the SBs, and both the fresh whole blood, and the anti-coagulated ovine blood. Sections of the NBR and NRL gloves were cut off and placed onto the stretching device used in Chapter 4 (Section 4.3.1) to flatten the material and secure it in place. Contact angles were measured via a contact angle goniometer (ramé-hart, model 100-06) using the sessile drop method used in Chapter 4 (Section 4.3.1). The previous work also showed that the contact angle is unaffected by the strain of the material. Thus, the material was studied in the 'unstrained' condition.

9.3.6 FTIR

FTIR (described in Chapter 5, Section 5.3.1) was used to assess whether binding to the gloves was similar between the ovine and the whole blood samples. Whole human blood (0.4 ml, acquired by the lancing device in Figure 9.1), and ovine blood (0.4 ml) was syringed onto the NRL and NBR gloves, separately (4 samples in total). The samples were left to dry for 30 minutes before washing the solutions in DI water. The gloves were then scanned on the FTIR (Thermo Scientific, Nicolet iS5) in the 4000-600 cm^{-1} region with a scanning resolution of $4cm^{-1}$. Three samples of each glove and each blood source were obtained (12 scans in total).

9.3.7 Friction measurements

Anwer (116) previously analysed the friction coefficients of blood on a scalpel handle with a serrated surface on both the flat and serrated section. However, scalpels come with a variety of serrated patterns. In many cases, these patterns contain large areas of smoother material where fingers are placed. Therefore, for consistency and comparison to the previous work conducted in this thesis, the friction was measured using a polished steel strip, which was used to represent smooth metal in the medical profession (bedpans, smooth medical tools, trolleys etc.) and the pegboard pins in Chapters 6 and 8.

As with the previous tests (see Chapter 6 and 7), the gloved index finger pad of the sole participant (male, aged 28) was placed onto the metal strip (attached to the AMTI force plate using double sided tape) at a 40° angle. The finger was held for 2-3 seconds at the desired force before it was moved down the strip. The forces used were chosen based on the grasping forces discussed and used in previous chapters, with target loads of 1, 2, 3, 4 and 5 N (189). The static friction was assessed for this work, as this is considered more relevant to studies of this ilk with medical examination gloves (114, 116). The friction assessments were carried out on the ovine blood and the synthetic bloods only. The fresh blood volume obtained from the lancing device was not enough to carry out frictional assessments, as previously stated.

Blood and SB deposition

Contaminants were deposited in the same manner as in Chapter 7, whereby the finger was placed into the solution, up to the proximal-intermediate interphalangeal joint, for 10 seconds (Figure 9.2). Prior to putting the finger into the glove, the glove was ensured to fit around the finger, meaning no loose material was present. The finger was then removed, the excess shaken off and the friction analysis conducted. All contaminants were tested at room temperature (23.1-24.8°C), with the exception of the blood, which was heated to physiological temperature 37°C (±1.5) via a water bath and monitored with an infrared thermometer (Raytek, RSCMTFSU ±0.5°C).

Figure 9.2. Application of solutions to the glove materials

Weight deposited

The mass transfer of blood was measured by analysing the weight transferred to the glove. The gloves were weighed using a 5 point balance (Analytical Sartorius ±0.0001 g) and then the blood was applied following the application method. The gloves were then weighed again to determine the mass. Three of each glove were assessed with each SB and the ovine blood. As is visible from the image in Figure 9.3, the distribution of blood onto the glove is not homogenous, i.e. the blood pools in some areas and is thinner in others. Therefore, the film thickness has not been calculated (as in Chapter 7) due to the visually uneven dispersion.

Figure 9.3. Blood deposited onto the finger

Temperature changes

As with the mucin in Chapter 7, the blood was measured for changes in temperature when removed from the water bath once transferred to the finger. This was measured five times to obtain an average. The temperature was found to drop to an average of 34.6 (±0.32) °C. As with the mucin used previously in Chapters 7 and 8, the proteins in blood are sensitive to heat and the interactions with their surroundings (290, 296, 298). Thus heating beyond physiological temperature may have changed some of these interactions with the glove materials, leading to differences in bonding, triboelectric interactions, and drying properties (299). Furthermore, in scenarios where blood has contaminated medical examination gloves, the blood has usually already left the body. Thus, it will have dropped in temperature, as seen in this study, whereas the physiological temperature would be more appropriate to maintain when assessing surgical gloves, as the gloves are likely to be in a more temperature regulated and controlled environment.

Drying

In order to assess the drying efficacy, 0.5 ml of blood was syringed onto sections (approx. 5.0 × 5.0 cm) of the glove materials and rubbed with the syringe to spread the sample. This was weighed and then left to dry on the weighing scales (Analytical Sartorius ±0.0001 g), with the weight taken every 30 seconds to assess the drying time over 5 minutes. This was carried out 5 times for each material.

9.3.8. Statistical analysis

In order to assess the similarities of each synthetic sample to the ovine blood, two-tailed paired t-tests were performed on the CoFs at each of the target loads (300). The null hypothesis states that no differences exist between the SB and the blood. Therefore, a p-value greater than .05 shows that there is no evidence of a difference between the SB friction and the whole ovine blood. T-tests were also carried out on the contact angles of human blood and ovine blood to assess how similar the initial contact behaviour is between the two.

9.4 Results

9.4.1 FTIR

The spectra of the human and ovine bloods are shown in Figure 9.4 with NBR and Figure 9.5 with NRL. As is visible there are changes present to the spectra between the clean, uncontaminated NBR and the blood contaminated NBR. Major changes to functional groups and peak absorbances have been highlighted on both figures. There are some minor absorbance differences between the two blood types on both glove materials, but the results show very similar spectral patterns, indicating that in both materials, similar changes also occur. When blood is present in both glove materials the amide (NH) peaks around 6340-6390 cm^{-1} disappear, and a stronger presence of the hydroxyl (OH) is noted in the broad peaks at 3500-3150 cm^{-1}. A carbonyl (C=O)/Diene (C=C) peak is also present when blood has contaminated the surface of both materials at around 1650 cm^{-1}. The presence of two peaks at 1575-1540 cm^{-1} indicates amide C=C stretching. However, this noticeably then becomes one peak when contaminated with blood, indicating the presence of a carboxylate (COO-) around the

1540 cm^{-1} wavelength. The final major peak change is seen with the dissolution of the ester C-O-R) stretching/Aliphatic amine (C-N) peaks present around the 1052-1010 cm^{-1} region when the gloves are contaminated with blood (209, 210, 265). The peaks present around the 2360-2340 cm^{-1} region indicate the presence of CO_2 in the atmosphere and are not regarded as changes to the surface in these results. The changes in spectra show that blood has either bound to the surface chemically or chemically modified the surface. After washing both of the materials, the gloves were found to have discoloured, thus it is likely that blood has bound to the surface and cannot be washed off.

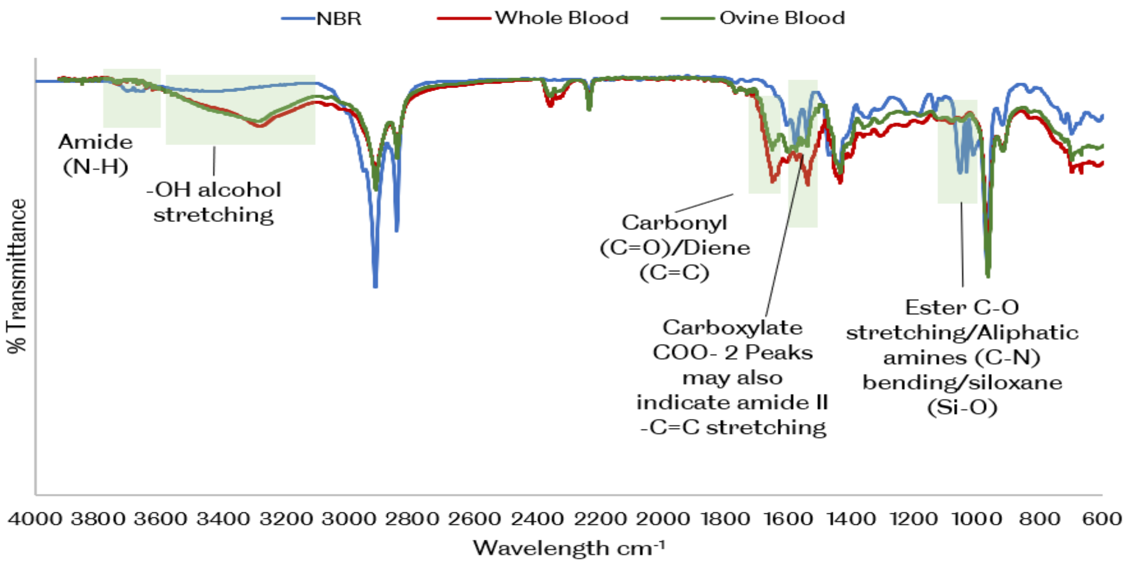


Figure 9.4. FTIR spectra of the NBR gloves and gloves contaminated with ovine and human blood

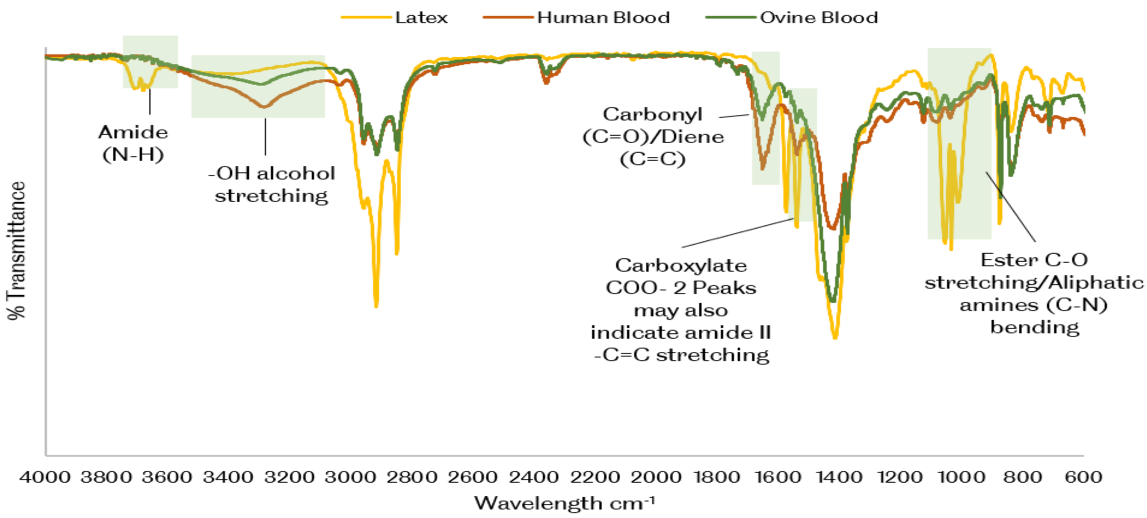


Figure 9.5. FTIR spectra of the NRL gloves and gloves contaminated with ovine and human blood

9.4.2 Material characterisation

The first SB formed (SB1) formed a rigid gel-like substance. This rendered the material unusable for the purposes of this experiment, thus no testing has occurred using SB1. However, the substance was further diluted to make a 6th and 7th synthetic blood (SB6 and SB7), as described in the methodology (Table 9.1). The overall results of the density measurements, pH, and contact angles are shown in Table 9.2. As can be seen similar results are observed for the pH of the solutions. Putting them in the neutral range, with slightly basic properties, which is similar to that observed with the blood.

Table 9.2. Properties of the synthetic bloods and blood. Red cells indicate the results that are not close to blood. Amber indicates results which are close to that of blood, and green indicates little to no difference with blood.

Solution	pH	*ρ* (kg/m³)	η (mPa-s)	Contact Angle (°)	
				NBR	NRL
SB1	7.19	Solution formed a thick gel – unsuitable for further testing			
SB2	7.27	1071.90 (±1.32)	6.49 (±0.03)	42.67 (±8.74)	135.67 (±10.26)
SB3	7.29	1010.99 (±0.37)	1.45 (±0.03)	43.00 (±10.15)	107.67 (±6.11)
SB4	7.25	1031.85 (±0.17)	1.18 (±0.01)	26.33 (±2.08)	122.33 (±4.36)
SB5	7.32	1043.62 (±2.47)	3.67 (±0.00)	43.67 (±1.53)	97.00 (±3.06)
SB6	7.29	1035.57 (±0.17)	3.45 (±0.04)	37.33 (±7.57)	125.00 (±12.53)
SB7	7.22	1030.51 (±0.11)	2.98 (±0.01)	33.00 (±2.65)	102.90 (±6.28)
Whole Ovine Blood $^{\Delta}$	7.31	1052.38 (±2.15)	3.38 (±0.00)	32.00 (±4.92)	95.00 (±9.18)
Whole Human Blood	7.35-7.45*	1025-1060*	3.00-4.00*	33.00 (±2.65)	92.00 (±11.87)

Δ = testing carried out at 37°C. ± indicates standard deviation. **averages obtained from literature*

Density

The density of each of the samples is shown in Figure 9.6. The results show that SB2 (ρ= 1071.90 ± 0.17 kg/m³) and SB3 (ρ= 1010.99 ± 0.37 kg/m³) do not fit into the density range of the blood provided in the literature (shown in faded red on Figure 9.6). However, there is little variation in the density between the SB4, SB6, and SB7. The closest match of density to the ovine blood is SB5, which is also the only SB to have no significant difference to the blood following a paired t-test ($t(2)=-1.010$, $p=.158$, Table 9.3).

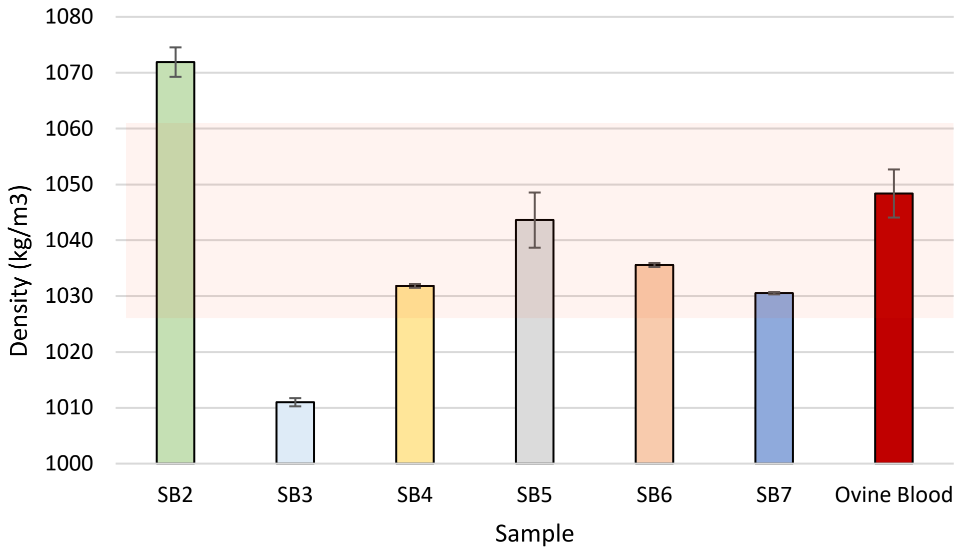


Figure 9.6. Density of synthetic bloods and ovine blood. Opaque red band indicates density range of whole human blood in the literature. Error bars denote standard deviation.

Table 9.3. Paired t-tests, comparing the developed SB to the measured ovine density.

Sample	t-test
SB2	*t(2)=8.149 p=.001**
SB3	*t(2)=-20.990 p=<.001**
SB4	*t(2)=-9.837 p=.006**
SB5	*t(2)=-1.010 p=.158**
SB6	*t(2)=-7.626 p=<.001**
SB7	*t(2)=-10.740 p=.001**

**indicates statistically significant differences (p<.05)*

Viscosity

The viscosities between the solutions have some differences (Figure 9.7). The solutions range from 6.49 to 1.18 mPa-s within a temperature range between 23.1-23.5°C. The results indicate that SB2 is the most viscous of the solutions at 6.45 (±0.03) mPa-s. This is likely due to the amount of flour present in the solution. The samples were homogenised by mixing/shaking. However, in this solution, it was found that the suspended flour quickly settled to the bottom of the mixture. The average reported viscosity of whole blood is reported to be between 3-4 mPa-s, which is highlighted on the graph in Figure 9.7. Only SB5 (3.67 ±0.00 mPa-s) and SB6 (3.45 ±0.04 mPa-s) fall into the average viscosity range of blood, whilst SB7 is on the verge at 2.98 mPa-s (±0.01). Although, none of the viscosities measured show statistical similarities to the ovine blood, SB5, SB6 and SB7 all show similar results to the ovine blood (*p<.05*, Table 9.4).

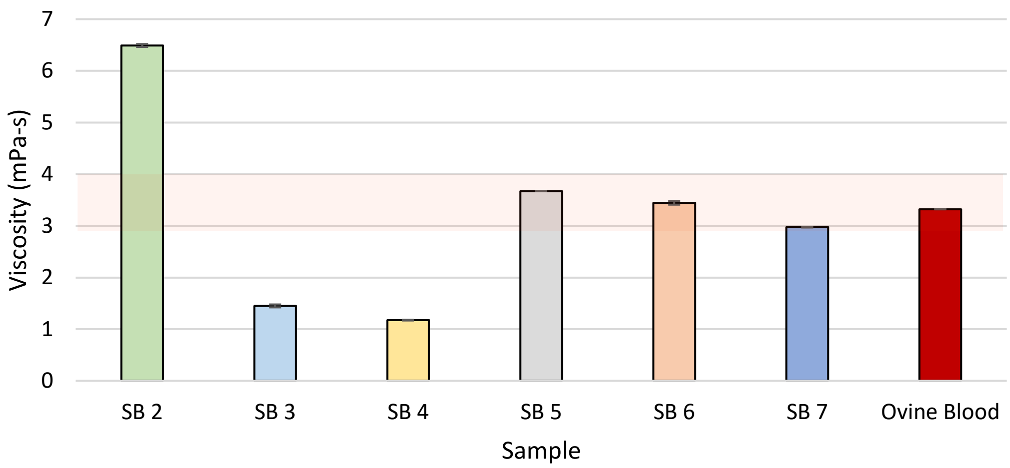


Figure 9.7. Viscosity of synthetic bloods and ovine blood. Opaque red band indicates viscosity range of blood in the literature. Error bars denote standard deviation.

Table 9.4. Paired t-tests, comparing the developed SB to the measured ovine viscosities.

Sample	t-test
SB2	*t(2)=-230.409 p=<.001**
SB3	*t(2)=140.750 p=<.001**
SB4	*t(2)=288.900 p=<.001**
SB5	*t(2)=-37.123 p=<.001**
SB6	*t(2)=-7.506 p=.016**
SB7	*t(2)=40.442 p=.001**

** indicates statistically significant differences (p<.05)*

Contact angles

The results for contact angles with the SB, ovine and human blood are shown in Figure 9.8. When whole human blood was exposed to the NBR surface, there is a good surface wettability with an average contact angle of 32.78° (±1.79). An example of SB4 in contact with the NBR is shown in Figure 9.9 (a). When in contact with NRL, there is a lower surface wettability with an angle of 92.0° (±11.87). An example of SB5 in contact with the NRL is shown in Figure 9.9 (b). The results obtained from the ovine blood have similar contact angles, and no statistically significant differences are shown between the two samples with human blood (NRL *t(2)=0.451*, *p=.949* ; NBR *t(2)=0.707*, *p=.816*). The SBs show similarities through their results in the NBR samples, with the exception of SB4 which has a lower contact angle on average (26.3° (±2.08)). As this solution contains flour, the solution has become colloidal, with suspended particulates of flour, this could affect the contact angle of the solution with the gloves. However, SB2 contains more flour than SB4, but does not exhibit the same behaviour. When applied to NBR, SB4 and SB7 have a similar contact angles to real blood at 33.0° (±4.92). When applied to NRL, SB5 (97.00° (±9.18) and SB7 (102.90° (±6.28)) have similar contact angles to ovine blood at 95.00° (±9.18). Paired t-tests show no statistical differences to any of the contact angles with the ovine blood for both materials (*p>.05*, Table 9.5). However, a significant difference is found between SB5 (43.66°) and the ovine blood in the NBR material (*t(2)=-6.407*, *p=.007*).

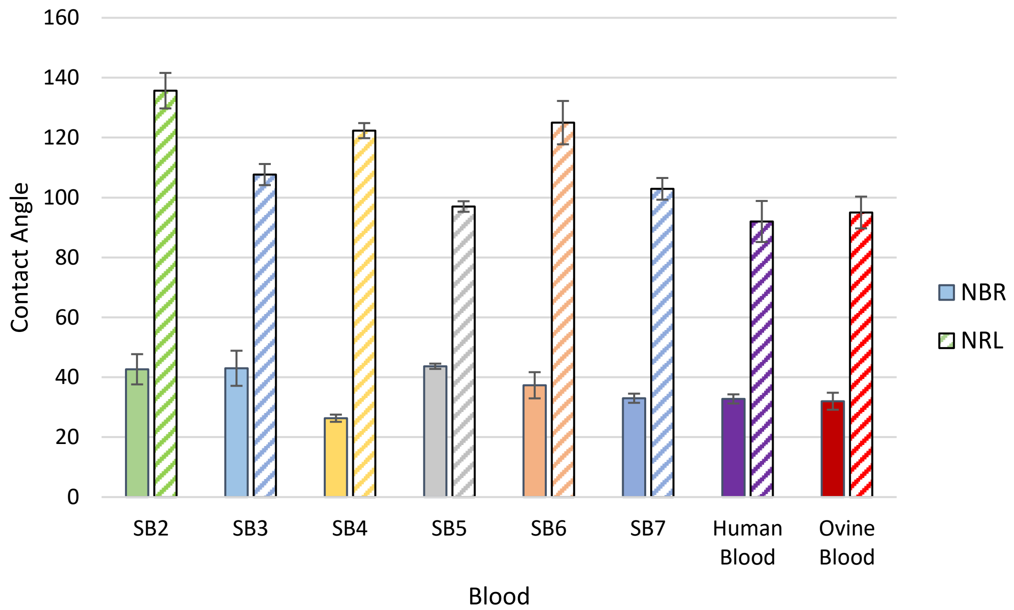
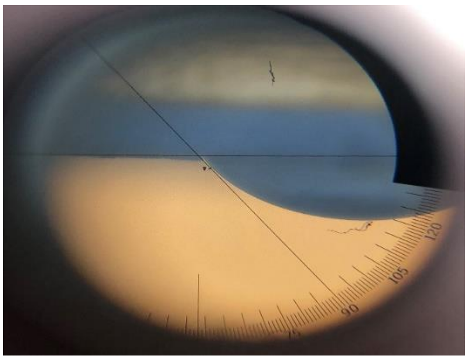


Figure 9.8. Contact angles of synthetic bloods, ovine blood, and human blood. Error bars denote standard deviation.

a) 

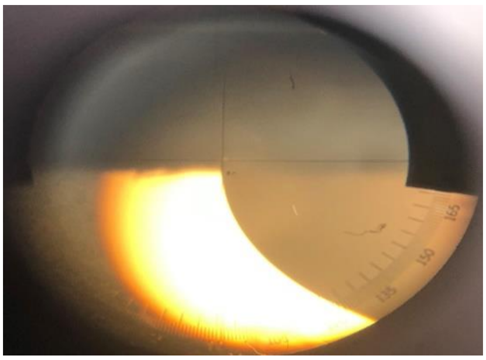
b) 

Figure 9.9 (a-b). Contact angles of a) NBR and b) NRL. The lower contact angle in NBR indicates a surface with hydrophilic properties whilst the NRL indicates hydrophobic with high contact angles, as observed with all of the synthetic bloods.

Table 9.5. Paired t-tests, comparing the developed SB to the measured ovine contact angles as well as comparing the human to the ovine blood.

Sample	Glove t-test	
	NBR	**NRL**
SB2	*t(2)=-1.834 p=.279*	*t(2)=-3.919 p=.055*
SB3	*t(2)=-1.651 p=.161*	*t(2)=-0.841 p=.551*
SB4	*t(2)=-1.546 p=.135*	*t(2)=-6.146 p=.042*
SB5	*t(2)=-6.407 p=.007**	*t(2)=-2.377 p=.134*
SB6	*t(2)=-0.935 p=.520*	*t(2)=-2.284 p=.134*
SB7	*t(2)=-0.621 p=.686*	*t(2)=-1.011 p=.992*
Human blood	*t(2)=0.707 p=.816*	*t(2)=0.451 p=.949*

**indicates statistically significant differences*

Deposited material

The amount of each SB and blood deposited onto both glove materials, following the application method, is shown in Figure 9.10. Similar amounts of the blood and SB's are deposited onto both of the glove materials. NRL is shown to have slightly less of each solution transferred to the gloves, which was also noted in Chapter 7 and 8. The average amount deposited for all SBs onto the NBR is 0.101 (±0.006) g, whereas the NRL was found to have 0.089 (±0.008) g deposited. The largest noted difference between the two materials is with SB4. As SB4 was a suspension of flour in a sugar solution, this could have been due to the amount of flour getting stuck to the glove material. In the NBR, 0.097 (±0.005) g was found to stick to the glove, whereas 0.076 (±0.012) g was found on the NBR. More ovine blood was also found on the NBR (0.090 (±0.01) g) when compared to the NRL (0.073 (±0.004) g). Statistically significant differences are not found between the weight of blood and the weight of solutions SB4, SB5, SB6, and SB7 when on the NBR material (*p>.05*, Table 9.6). SB4 shows no statistically significant difference to the blood deposition when on the NRL (*t(2)=0.561*, *p=.494*).

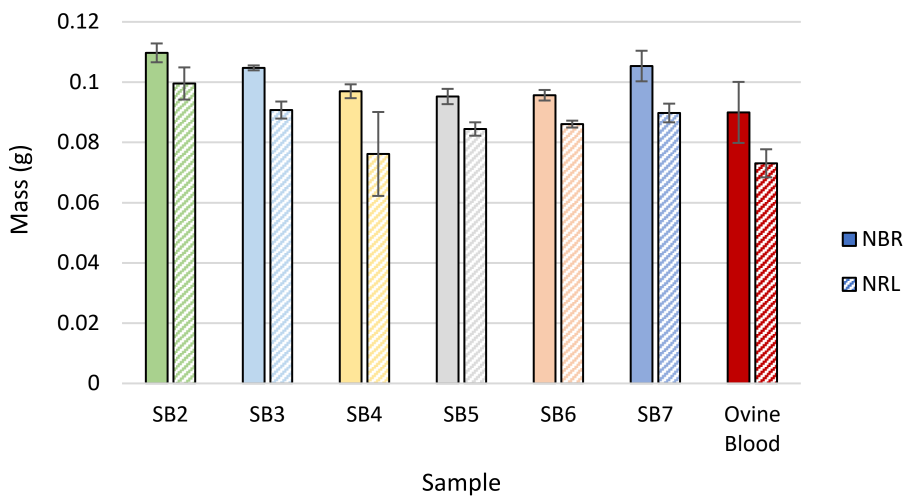


Figure 9.10. Amount of SB, and blood deposited onto the NBR and NRL glove materials. Error bars denote standard deviation.

Table 9.6. Paired t-tests results of weight deposition between ovine blood and each synthetic blood.

Sample	**Glove t-test**	
	NBR	**NRL**
SB2	*t(2)=-3.595 p=.024**	*t(2)=-4.627 p=.013**
SB3	*t(2)=-3.211 p=.032**	*t(2)=-5.208 p=.002**
SB4	*t(2)=-1.383 p=.282*	*t(2)=-0.561 p=.494*
SB5	*t(2)=-1.018 p=.452*	*t(2)=-3.736 p=.001**
SB6	*t(2)=-1.174 p=.365*	*t(2)=-5.476 p=.003**
SB7	*t(2)=-2.264 p=.168*	*t(2)=-4.477 p=.020**

**indicates statistically significant differences*

Drying

The results of blood drying show similar rates of evaporation for each of the materials (Figure 9.11), with the NBR having a slightly higher evaporation rate than the NRL. On average, the NBR has a weight loss of 0.06412 (±0.00199) g every 30 seconds, whereas the NRL lost an average of 0.05429 (±0.00123) g every 30 seconds.

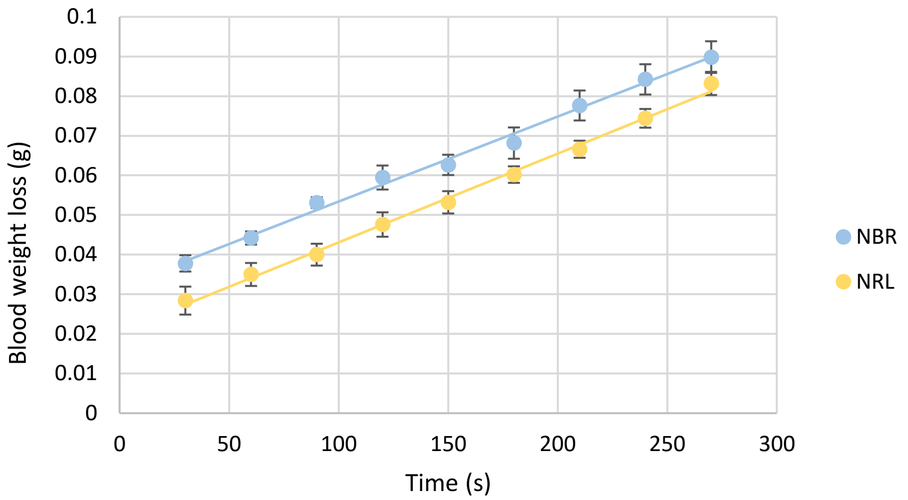


Figure 9.11. Evaporation of blood from the surface of the NRL and NBR materials

9.4.3 Friction

Resultant horizontal force and power fit laws were fitted to the data, and CoFs were calculated as per the preceding chapters in this thesis, using the equations in Chapter 4 (see equations 4.2-4.4)

9.4.3.1 NBR

Blood

An example of the raw data for the NBR with blood is shown in Figure 9.12. The friction results obtained from the uncontaminated NBR gloves are shown in Figures 9.13 (a-b) along with the blood contaminated glove friction. The addition of blood produces lower CoFs than for the dry condition. When contaminated, the behaviour is similar to the dry condition across the loads, as the CoF ranges between 0.72-0.67. The dry condition does, however, show a slight trend of increasing CoF as the load increases, which does not occur when the gloves are contaminated with the ovine blood (μ ranges 1.10-1.01 when dry). The decrease in friction is significantly different across each load following paired t-tests (1N *t(2)=3.318, p=.081;* 2N *t(2)=0.917*, *p=.935;* 3N *t(2)=-2.553, p=.125;* 4N *t(2)=-2.886*, *p=.102;* 5N *t(2)=0.934, p=.449*).

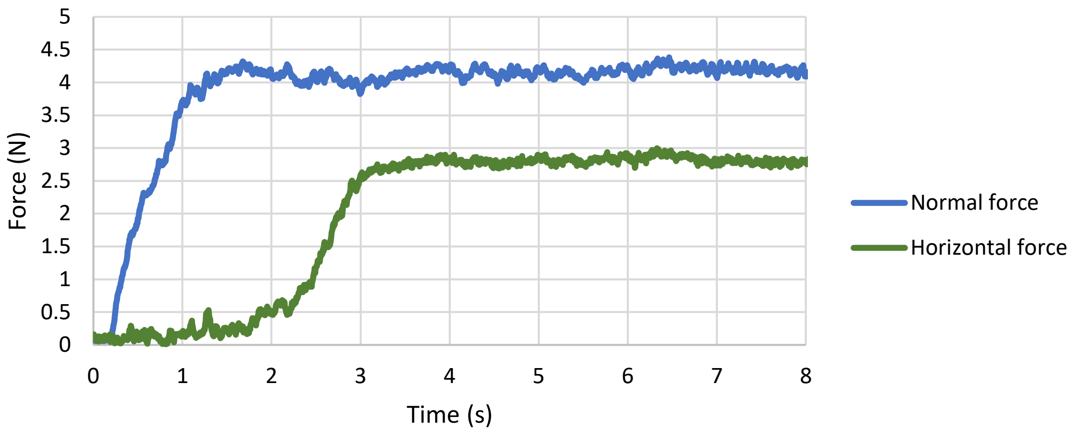


Figure 9.12. Normal and Horizontal force of the NBR glove contaminated with ovine blood at the 4 N target load on smooth steel.

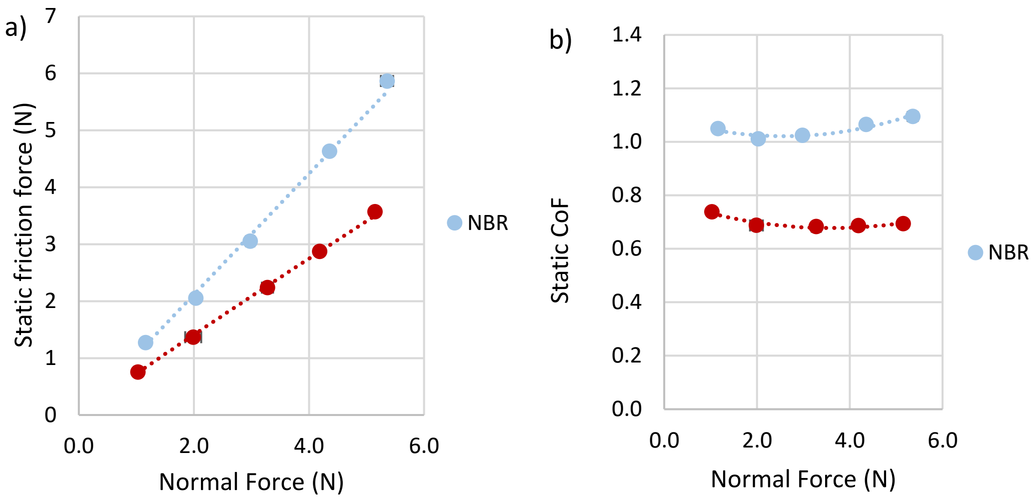


Figure 9.13 (a-b). Static friction (a) and CoFs (b) for dry NBR gloves and NBR gloves when contaminated with ovine blood on smooth steel. Error bars denote standard deviation.

Synthetic validation

The static friction of the NBR gloves when contaminated with the SB's and the ovine blood are shown in Figure 9.14 (a-b). SB3 has a consistently higher CoF on average across all of the loads when compared to the ovine blood sample. SB6 is higher at the 1 N load, and then lower as the load increases. SB5 and SB6 show similar trends in decreasing CoF over the increased load, whereas SB2 is the only solution which is shown to increase CoF over the load range. The CoF of SB4 also increases, however there is a decrease in CoF initially (1 N μ= 0.79 ±0.02; 3 N μ= 0.52 ±0.01; 5 N μ= 0.66 ±0.01). At the 1 N load SB4 (μ= 0.79 ±0.02) and SB7 (μ= 0.75 ±0.01) produce similar CoFs to the ovine blood (μ= 0.73 ±0.02). SB7 has similar CoFs to the ovine blood, exhibiting little friction differences across the range of loads. Due to the similarity in results, only SB7 has been tested for statistical significance (Table 9.7). The t-tests shows no significant differences between the blood and SB7, indicating similar CoFs at each of the target loads.

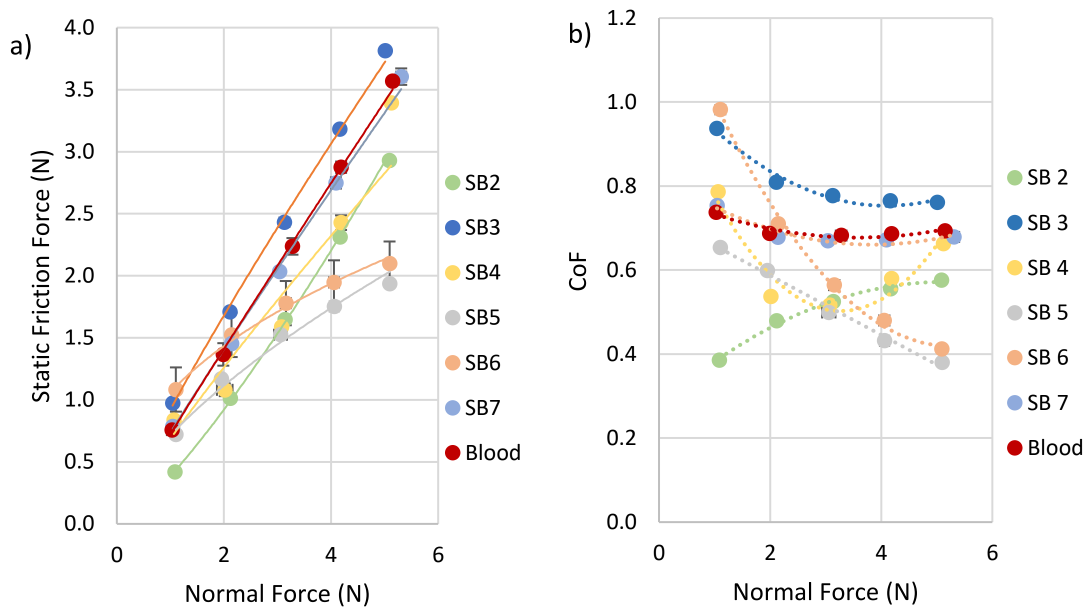


Figure 9.14 (a-b). Static friction (a) and CoFs (b) for dry NBR gloves when contaminated with synthetic bloods and ovine blood. Error bars denote standard deviation.

Table 9.7. Static CoFs obtained from SB7 and whole ovine blood with paired t-test results with NBR contaminated gloves.

SB7		**Blood**		**CoF t-test**
Load (N)	**CoF**	**Load (N)**	**CoF**	
1.04 (±0.04)	0.75 (±0.02)	1.03 (±0.07)	0.73 (±0.01)	***t(2)=0.142 p=.901***
2.14 (±0.04)	0.68 (±0.04)	1.99 (±0.14)	0.69 (±0.01)	***t(2)=1.634 p=.243***
3.04 (±0.01)	0.67 (±0.01)	3.28 (±0.10)	0.68 (±0.01)	***t(2)=-3.745 p=.065***
4.09 (±0.07)	0.67 (±0.07)	4.19 (±0.06)	0.69 (±0.01)	***t(2)=0.967 p=.436***
5.31 (±0.11)	0.68 (±0.09)	5.15 (±0.04)	0.70 (±0.02)	***t(2)=2.702 p=.114***

± denotes standard deviation

The 1N force is the force most observed with grasping and holding equipment lightly, therefore it could be considered more important that the friction at the 1N force needs to be similar between the synthetic and the blood (218). Figure 9.15 highlights the similarity in friction between SB7 and the ovine blood at the 1N target load. No statistical difference is found between the CoFs with SB7 showing a CoF of 0.75 (±0.01) and blood showing a CoF of 0.73 (±0.02). As shown in Table 9.7, the results are statistically similar following a paired t-test (*t(2)=0.142*, *p=.901*).

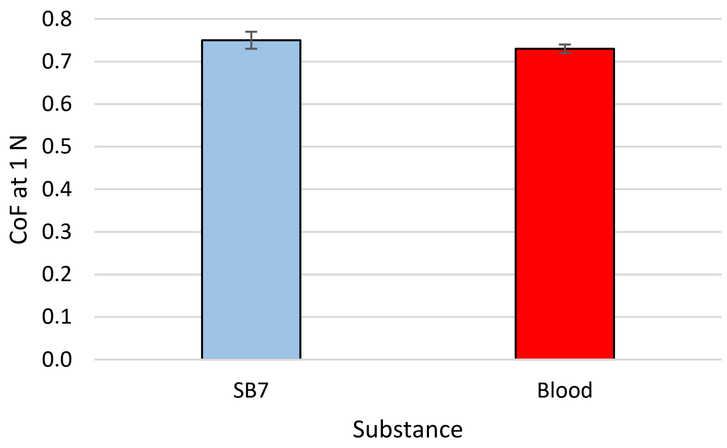


Figure 9.15. Comparison of the Static CoF at the 1 N target load for SB7 and ovine blood. Error bars denote standard deviation.

9.4.3.2 NRL

Blood

An example of the raw data for the NBR with blood is shown in Figure 9.16. The results comparing the dry NRL to the blood contaminated NRL are shown in Figure 9.17 (a-b). As with the NBR, the NRL is shown to decrease in friction. However, the decrease is far greater than observed in the NBR. This was also noted with the mucin protein used in Chapter 7. When blood is applied, the CoF is shown to be significantly greater (*p<.05*) than the dry condition between all of the loads. The greatest difference is observed between the 1N target loads. The CoF is shown to decrease by 1.44 when the gloves are contaminated by blood (dry μ= 2.15 ±0.02; blood μ= 0.71 ±0.01, *p=<.001*). As the load increases the CoF of the blood decreases slightly to 0.50 ±0.01. The CoF at all loads is shown to be significantly different (1N *t(2)=-64.246, p=<.001;* 2N *t(2)=-75.466, p=<.001;* 3N *t(2)=-238.713, p=<.001;* 4N *t(2)=-199.080*, *p=<.001;* 5N *t(2)=-331.705*, *p=<.001*).

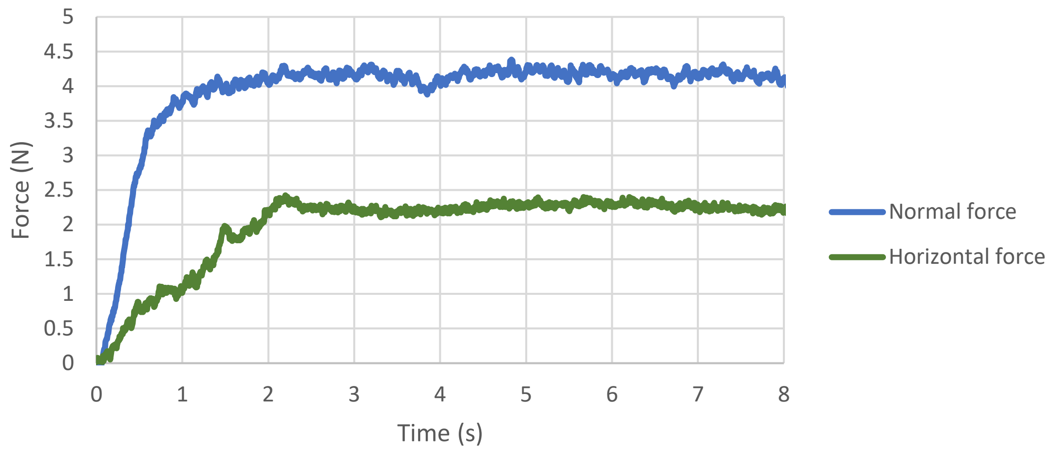


Figure 9.16. Normal and horizontal force of the NRL glove contaminated with ovine blood at the 4 N target load on smooth steel.

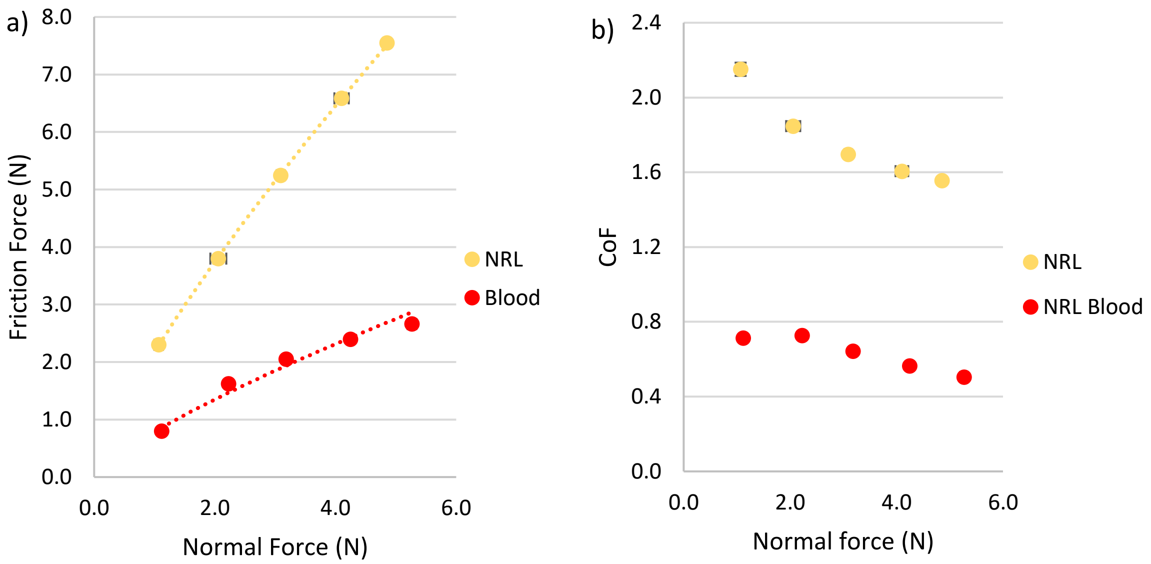


Figure 9.17 (a-b). Static friction (a) and CoFs (b) for dry NRL gloves and NRL gloves when contaminated with ovine blood on smooth steel. Error bars denote standard deviation.

Synthetic validation

The static friction results of NRL gloves are shown in Figure 9.18 (a-b). Noticeably the friction of the solutions is higher with NRL than with NBR. SB7 shows a sustained higher friction than all of the other SBs, with the exception of SB3 at the 1N load (SB3 μ= 1.82 ±0.01; blood μ= 1.69 ±0.01). With the exception of SB2, which behaved similar to the NBR material, and SB6, all SBs showed a trend of decreasing CoF with an increase in load. SB7 shows a sustained higher friction than all of the other SBs, with the exception of SB3 at the 1N load (SB3 μ= 1.82 ±0.01; blood μ= 1.69 ±0.01). Overall blood produces a lower CoF than the other SB's except for SB2 at 1 N (SB2 μ= 0.61 ±0.11; blood μ= 0.71 ±0.05). This similarity was found to be statistically similar (*t(2)= 1.593*, *p=.204*, Table 9.8). Statistical significance was found at each of the other loads (2-5 N, *p<.05,* Table 9.8). SB3 at 5 N has a similar CoF to the blood at 5 N (SB3 µ= 0.60 ±0.01; blood µ= 0.51 ±0.04), however this is statistically different (*t(2)=-11.269*, *p=<.001*). With the exception of SB2, which behaved similar to the NBR material, and SB6, all SBs had a trend of decreasing friction with an increase in load. SB7 shows a sustained higher friction than all of the other SBs, with the exception of SB3 at the 1N load (SB3 µ= 1.82 ±0.01; blood µ= 1.69 ±0.01).

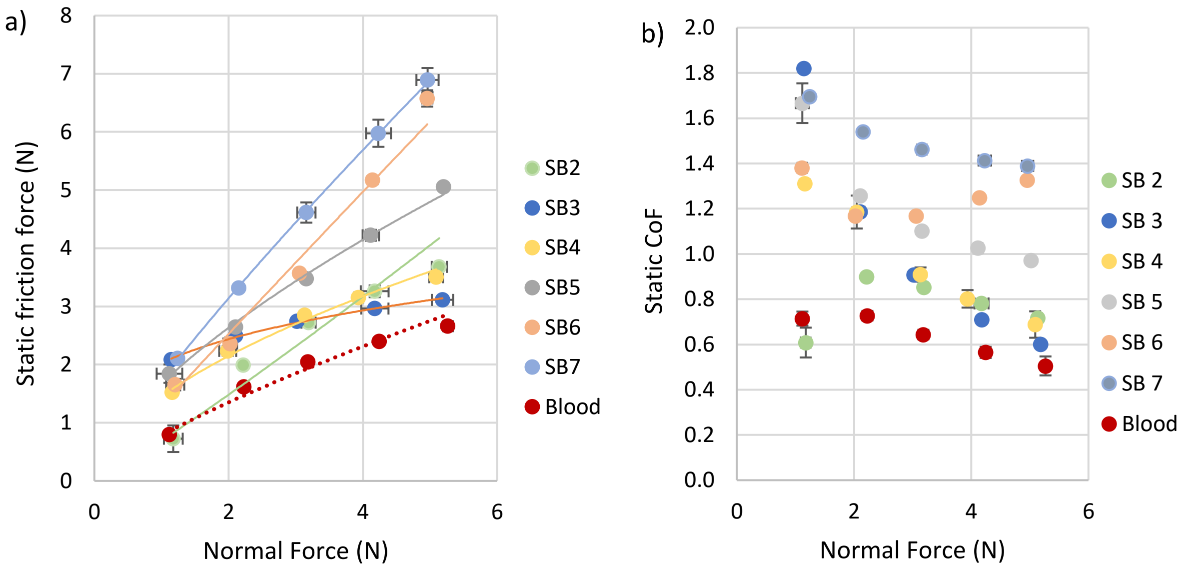


Figure 9.18 (a-b). Static friction (a) and CoFs (a) for dry NRL gloves when contaminated with synthetic bloods and ovine blood. Error bars denote standard deviation.

Table 9.8. CoFs obtained from SB2 and whole ovine blood with paired t-test results with NRL contaminated gloves.

SB2		**Blood**		**CoF t-test**
Load	**CoF**	**Load**	**CoF**	
1.18 (±0.14)	0.61 (±0.09)	1.12 (±0.05)	0.71 (±0.02)	***t(2)=1.593 p=.204***
2.20 (±0.05)	0.90 (±0.03)	2.23 (±0.04)	0.73 (±0.05)	***t(2)=-96.190 p=<.001****
3.12 (±0.11)	0.85 (±0.01)	3.18 (±0.04)	0.64 (±0.01)	***t(2)=-44.715 p=<.001****
4.18 (±0.21)	0.78 (±0.02)	4.25 (0.04)	0.56 (±0.02)	***t(2)=-24.545 p=<.001****
5.13 (±0.11)	0.72 (±0.01)	5.27 (0.07)	0.51 (±0.04)	***t(2)=-47.039 p=<.001****

*± denotes standard deviation *indicates statistically significant differences*

As with the NBR, focus should be placed around the 1 N load, for easier comparison. Figure 9.19 highlights the similarity in friction between SB2 and the ovine blood at the 1N target load. No statistical difference is found between the CoFs with SB2 showing a CoF of 0.61 (±0.11) and blood showing a CoF of 0.73 (±0.02). As shown in Table 9.7, the results are statistically similar (*t(2)=1.593*, *p=.204*).

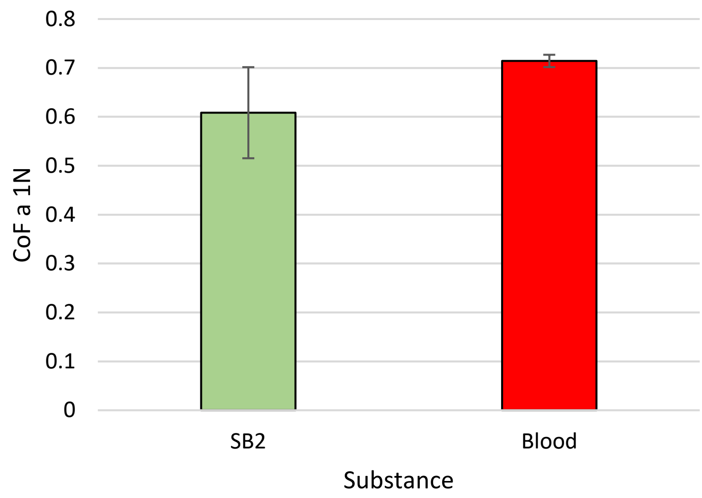


Figure 9.19. Comparison of the Static CoF at the 1 N target load for SB2 and ovine blood with NRL. Error bars denote standard deviation.

9.5 Discussion

9.5.1 Whole human and citrated blood

Many minor procedures exist where anti-coagulants are provided (301). Therefore, a part of this study was aimed at assessing if the chemical behaviour was the same between whole blood and anti-coagulated blood upon contact with the glove materials. The results indicate that the contact and reactions are similar between the two whole bloods used. The FTIR shows similar spectra for both the ovine and human blood in both NRL and NBR. This is likely due to the fact that the components of blood which are interacting with the gloves are the same for both samples, thus the spectra are similar. There is evidence of some sustained differences on the gloves surface once exposed to blood. These changes appear to be more prevalent in the NRL, as indicated by the greater differences in absorbances, likely to be because of blood protein and latex protein residue interactions. The initial contact of the bloods on the gloves also shows similar angles for both the NRL and NBR materials. It is shown that for this study, the chemical interactions between the blood and the glove are not dependent on the presence of an anti-coagulant. This means using the anticoagulated blood reflects the initial interactions that would be seen in a clinical situation.

9.5.2 Effects of blood on glove friction

The results obtained from the NRL gloves reflect those from the study by Anwer (116), which showed the friction increased by 0.2 when blood was applied to NRL gloves. The results of this study also show a decrease in friction, showing that at 1 N, the CoF decreases by 1.44. Although, at the higher loads, the material will conform and bend more, causing a difference in the way the materials both contact the surface, and behave under that load, which has been shown and discussed in Chapter 6. Anwer (116) used greater forces for their study with blood, which led to a lot of fluctuation in the applied load (between 22.8 and 35.3 N). This fluctuation is most likely due to the extraordinary amount of pressure being placed onto one finger. This in unlikely to happen in surgeries, as the load applied will be spread across the fingers holding the tool, and not applied to one particular area.

As detailed in Chapter 6, the nature of the glove is important to their function, and when drawing comparisons between studies. The gloves used by Anwer (116) were only declared as NRL gloves. No information was present on whether the gloves were examination or surgical, nor how well the glove fit the finger. The study also set out to compare double gloves to single glove use when contaminated, which would imply that the gloves were surgical as double gloving is most likely to be used here (133). A question around this research has been that if blood can be used for friction tests, should it be fresh whole blood, most commonly encountered in minor wounds, or blood with an anti-coagulant, more often encountered in surgeries and minor procedures (301)? Unfortunately, as discussed, no fresh whole blood was available for the friction assessments, it is unable to ascertain if major differences would be between present between anti-coagulated and fresh blood. It is certain that the blood will dry and clot upon exposure to the atmosphere, thus friction changes will likely occur (296). What this work does show, however, is that blood decreases friction in both glove materials in very different ways, as observed in Chapter 7 with the other contaminants used.

Blood-glove material interactions

The differences in frictional behaviour are more observable as the loads increase. At the 1 N load, the gloves have similar frictional properties when contaminated by the blood (0.71 for NRL and 0.73 for NBR). As revealed in Chapter 7, both the affinity of the contaminant for the gloves, and the electrostatic interactions, both play a pivotal role in the frictional properties of contaminated glove materials. Much like the contaminants used in Chapter 7, this study has shown that the blood has a higher affinity for the NBR, and a lower affinity for the NRL. This is exhibited by the contact angle of blood on the NRL being greater than 90° and then when being exposed to the NBR, the contact angle is less than 90° (302). As blood is a tissue composed of many individual components, each with their own affinity and aversion to the materials further interactions complicate the frictional properties. Protein affinity will change and compete with weak electrostatic interactions depending on the environment, which make it difficult to determine exactly what is happening over the course of the changing loads (136).

Electrostatic and chemical interaction

As with the contaminants used in Chapter 7, and the water in in Chapters 4 and 5, blood will form capillary bridges, induced by electrostatic interactions, between the metal counter-face and the gloves. Oliver and Barnard (303) showed that the charges on blood are strongly influenced by the blood electrolytes, which in turn will influence the overall charges, and thus, the attraction to the different glove materials. Therefore, the effects of the electrostatic charges play an important part in the lubrication and adhesion processes with blood. Blood has been shown to have a varied charge depending on how it is suspended and the environment. Overall, the general charge on blood is negative (298, 304). However, constituents of blood possess some positive charges (such as the haemoglobin protein (305)), which are dependent upon the surroundings of the molecules (such as ions, dissolved gases etc.) (306). Although the proteins and constituents are different, the blood proteins will behave very similarly to the mucin proteins. That is to say, as noted with the mucin in Chapters 7 and 8, charge repulsion and charge attraction play a major role in how blood will bind to the gloves and cause changes in frictional properties.

Also previously discussed in Chapter 7, the triboelectric series places NRL as a negatively charged species and NBR as a positively charged species (14, 248). Therefore, more migration of the blood will occur towards the NBR material, which is seen by the contact angle and surface wetting as well as the higher mass being deposited onto the glove material. In the performance tests carried out in Chapter 8 with the mucin, this aided the dexterity and sensitivity. As the drying properties of blood are different, and tend to form gels which have greater tack than the mucin (297), it would be prudent to assume the same increase in performance would be present. But it can be presumed that differences in performance measures when different glove materials are contaminated with blood would be apparent, as this has been previously observed with the mucin protein in Chapter 8. It is, however, important to note that in both materials, the CoF drops to around 0.6-0.75 in both material, therefore it is possible that the presence of blood is similar, regardless of the glove material being used. This suggests the lubrication of the blood is an important factor, not just the chemical interaction. This means that a single synthetic blood being developed needs to be good enough to pick up the minor differences which exist between the friction with the two materials.

Blood drying and evaporation

In emergency situations where blood is present, there is likely to be dried blood already present which may not contaminate the gloves. However, once the wet blood has contacted the gloves, the probability of that blood drying is high. The drying property is also a function of the coagulation of the blood, which begins to occur once the blood has been exposed to a different environment. In coagulation, the fibrin proteins cross-link and form harder, solidified structures whilst the evaporation of water causes platelet adhesion and aggregation. This leads to gelation, and then solidification of the blood material (307). Laan, Smith, Nicloux, *et al.* (296) shows that, when blood pools, the substance undergoes two drying stages. The first of which is where the evaporation rate of the water increases towards zero. In the second stage, the liquid/gel diffuses the vapour to the surface of the material. Subsequently, the blood dries out and becomes a sticky gel, before becoming a solid mass through further evaporation. However, the study was looking at blood pooling, rather than smaller amounts of blood already applied to a surface. It is reasonable to think that since the blood is present in a smaller, thinner layer on the surface of the glove material, the drying process would be quicker in the study conducted here. Nonetheless, the drying process is slower at standard room temperature when compared to extreme conditions, thus is not likely to have a great affect in this friction study (297).

The reason for the difference in evaporation rate could be due to the affinity of the blood for the NBR surface, which could push the water to the surface, inducing a quicker evaporation than that seen with the NRL (296, 307). In standard examinations, where the gloves are exposed to blood, there is a greater likelihood that over time the frictional properties will change, due to the gelation, evaporation and ultimately drying of the blood. Neither this study, or the study by Anwer (116), looked into the effects of this. This study is looking more at examination gloves, which are more likely to be changed before the blood fully gels and turns into a tacky film. However, this depends on the volume of blood and the procedures involved, so may be of relevance for future work. The synthetic bloods developed will also undergo some evaporation, however, this was not explored here as the main constituent is water, so it was thought the evaporation would have less of an effect over the course of these studies.

9.5.3 Protein behaviour with gloves

Given that mucin and blood are both protein based substances, it is also important to compare the results from this chapter, and those observed in Chapter 7 when the gloves were contaminated by mucin. Although there are some differences, which are shown in Figures 9.20 (a-b), there are also similarities in the pattern of behaviour between the blood and mucin. At the 1 N target force, CoFs are shown to be similar between the two substances on both materials. This has been highlighted in the bar graph in Figure 9.21. The similarities in behaviour are likely to be due to the resemblances with the interaction. Both mucin and blood are primarily composed of water and proteins (234, 279). This strongly implies that the protein interaction and attraction/repulsion is of significance when studying the friction properties. Further work should be conducted looking at a range of protein based contaminants to fully understand the behaviour of the proteins under the load range. It does appear that at the lower load, more representative of a grasp force (189), a similar behaviour and friction coefficients are observed between the two materials with the proteins. It may be that the protein behaviour is similar when exposed to each material, which leads to a similar friction behaviour across the range of bodily fluids of the same ilk.

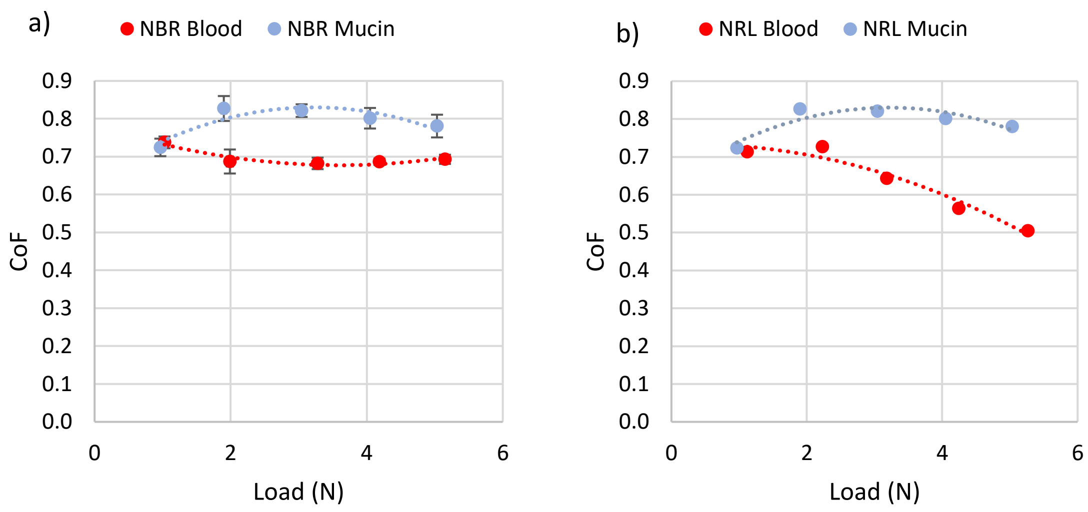


Figure 9.20 (a-b). Friction of blood and mucin over the 1-5 N load range with NBR (a) and NRL (b).

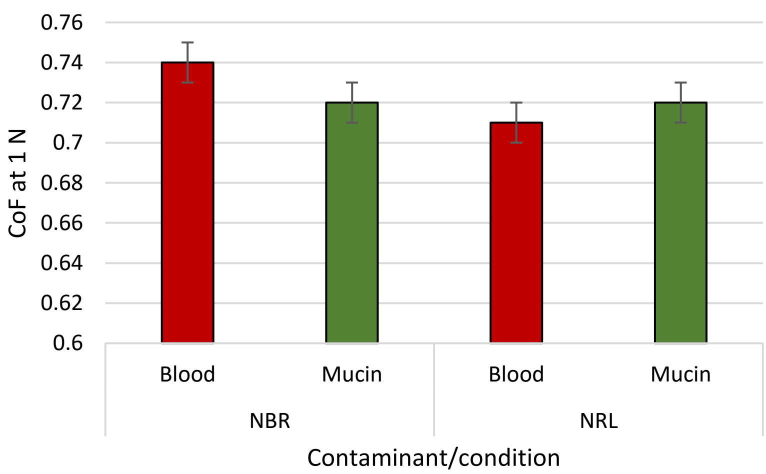


Figure 9.21. Static CoF for blood and mucin at 1N. Error bars denote standard deviation.

9.5.4 Synthetic blood development

The physical properties of the SBs are very similar to that of the blood, but none are an exact match. However, the density, contact angles and viscosity are deemed close enough to be similar to that of blood, with the exception of the gelatinous SB1. Of the 6 tested SBs, the frictional behaviour observed was different, especially between glove materials. Friction coefficients are shown to have little variance over the load range with the NBR material. On the other hand, the NRL materials show greater differences with friction over the loads. This pattern in behaviour of little change over the load range with NBR, but NRL exhibiting greater variation was also noted when using contaminants on the various surfaces in Chapter 7. There are two major categories that the SBs can be placed in. Those that contained particulate suspensions, and the more homogenous sugary solutions. Both of these types of solutions appeared to exhibit very different behaviours to each other.

Particulate solutions

The difference in frictional properties and behaviour over the load range is due to both the interaction with the materials and the individual constituents. However, when compared to the NRL, the NBR CoF range does not vary all that greatly. For example, in SB2 where flour is present, the friction goes from a low CoF (μ= 0.40) to a higher CoF (μ= 0.57) in the NBR, which is similar to the NRL (μ= 0.52 at 1 N; μ= 0.68 at 5 N). The presence of flour, which is undissolved, can cause both an increase and a decrease in friction. The friction will be low at a lower load as flour separates the two surfaces, which allows the glove to move easily down the counter surface in a ball-bearing fashion. On the other hand, as the force increases, the fine flour particles will fill asperities, increasing contact area or increase the occurrence more concentrated pockets of flour particles. This is dependent on how much of the flour is present between the glove material and the metal. This is shown schematically in Figure 9.22.

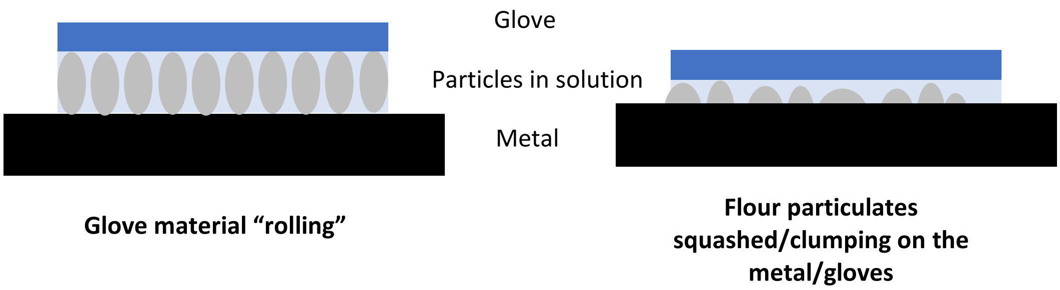


Figure 9.22. Behaviour of flour particulates under an increasing load.

Due to the hydrophilic nature of the NBR, this will bring the moisture closer to the surface, and in effect, hold some of the particulates there, causing greater separation of the metal and glove material. This is evidenced by the lower friction observable in the powder containing SB's with the NBR. In the NRL however, the moisture is pushed away because of the hydrophobic nature of the material, which could push out some of the suspended flour particles as more load is applied, hence a greater observed friction with the NRL. The CoF also shows a decrease with the increasing load in the NRL, which could be due to the water being pushed out and leaving more powder. Furthermore, AFM of the NRL gloves, in Chapter 7, showed greater gaps between the bulk glove materials, and it was hypothesised that this allows more contaminant to be pushed into the material under greater loads, which increased the friction in the NRL over the NBR material, in some cases. This behaviour is also observed in the SB4 solution at the lower loads, but not to as great and extent, as less flour was present, and the solution was of a more viscous consistency than SB2.

Sugary solutions

The greatest difference in friction and blood is observed with SB3, which is composed primarily of diluted sugar syrup, although not too viscous (compared to other sugar solutions), the result was a sticky watery solution. Due to the simple sugary nature of the material, the CoF is shown to be the highest in the NBR materials as more adhesion will occur. However, in the NRL, the CoF decreases with load. As described with the flour containing solutions, this is likely to be down to the repulsion of the SBs from the NRL surface. However, the interaction of the SBs with the NBR gloves produces very little differences over the load range in this work. Of the SB1 diluted samples (SB6 and SB7) there are varying behaviours between the two synthetics. In the NBR, SB6 acts very similar to SB5, exhibiting the highest friction coefficient at the low load, possibly because the primary ingredients are sugar and the thickening agent (methyl cellulose), which produced similar behaviour to the sugary solution of SB5.

9.6 Synthetic blood validation

SB7, which was only a quarter of SB1 mixed with water, had the highest friction along loads 2-5 N in the NRL gloves. However, in the NBR gloves, the CoFs produced are very similar to the blood. The synthetic solution was so similar that there were no statistically significant differences found between the two substances at each of the load used. This shows that a diluted mix of simple sugars can be used in lieu of blood for friction analysis across a 1-5 N load. However, this is only pertinent to the NBR gloves, as shown in the summary table (Table 9.9). With the NRL, none of the synthetic fluids matched the behaviour of the blood over the load range. However, there was a similar result produced between the blood and the flour based liquid of SB2 at the 1 N load. Due to the disbursement of the flour particulates when applied to the finger, it was presumed the similarity in friction may have been a random correlation. In essence, the amount of flour and mucin contained to the finger during the dipping procedure added is random. However, multiple repeats show similarities to the ovine blood the 1 N target load. It was found to get this match, the solution had to be homogenous, otherwise the friction was too high. Further work would have to be carried out with the solutions find a solution with a similar behaviour at a higher load with the NRL. Further work would have to be carried out with the solutions find a solution with a similar behaviour at a higher load. However, for the purposes of industry checking how the blood has modified behaviour, looking at the 1 N load, which is more simulative of gripping forces (189), would suffice to show the effects of contaminants on the frictional modification of gloves.

Table 9.9. Summary of synthetic bloods which have a similar CoF to blood on each of the glove materials along with their properties.

Glove Material	**NBR**	**NRL**
Synthetic Blood	SB7	SB2
Synthetic Blood Constituents	2.25g glucose syrup 1.25g methyl cellulose 0.25g sodium chloride 1.5 ml glycerol 45 ml DI water (Take ¼ of solution and dilute with 40 ml of water)	7.85g plain flour 1g glucose anhydride 0.15g porcine gastric mucin 34 ml DI water
PH	7.22	7.27
Density	1030.51 (±0.11)	1071.90 (±1.32)
Viscosity	2.98 (±0.01)	6.49 (±0.03)
Contact Angle	33.00 (±2.65)	135.67 (±10.26)
Static CoF at 1 N	0.75 (±0.02)	0.61 (±0.09)

± denotes standard deviation

Further work is also needed to explore the existence of an ideal substance which can give similar frictional properties to blood with both glove materials. The solutions used here were adapted and changed from one study only, which looked at viscosity (Millington paper). It is possible that, by adjusting the constituents in solutions made in this work, a better match for the frictional properties of both glove materials could be found. The aim of this study was to remove the requirement for animal blood to prevent storage issues. However, porcine gastric mucin was used as a thickening agent in the SB2 solution after finding the solution visually watery. This could draw some ethical quandaries, as the product is from animal origins. This could be substituted with other solution-thickening ingredients, if required. However, it could be argued that, as companies are turning more towards the NBR material (38, 43), the work regarding the NBR material with SB7 is more pertinent to the assessments required in manufacturing. This solution is solely comprised of sugary water, using ingredients that are easy to obtain.

9.7 Conclusions

A summary of the findings of this Chapter are shown in Table 9.10, detailing the CoF differences when gloves are contaminated, compared to dry, and surmising the SB's which closely match the CoFs of the different blood contaminated glove materials. SB2 and SB7 have very different constituents, which is less than ideal, especially for industry preparation, and quick testing. Further work is required to find a synthetic blood that works for both materials.

Table 9.10. Summary of results comparing dry gloves to blood contaminated, and the SB which replicates the frictional properties of blood across all loads and the 1 N target force.

	Glove material	
Friction tests	**NBR**	**NRL**
Blood friction	Decrease	Decrease
SB match at all loads	SB7	None
SB match at 1 N	SB7	SB2

The findings of this chapter are as follows:

- Blood that possesses anti-coagulants has the same chemical interaction with NBR and NRL gloves as fresh whole blood. In addition, spectral results show that gloves exposed to blood are contaminated permanently, as blood has shown to bind to both the NBR and NRL materials, causing changes to the surface chemistry. This binding is similar for both the fresh and blood and anti-coagulated blood.
- The friction of gloves is reduced when blood is exposed to both the NRL and the NBR gloves. However, a greater reduction in friction is observed in the NRL. It is important to note that when the blood is applied to both materials, the friction is reduced to similar levels due to the overriding effect of blood being present.
- The blood used in this study has a similar behaviour and frictional properties to the mucin used in Chapter 7. Due to the presence of proteins, and conformation changes in these proteins, being responsible for changes in viscosity when drying, it is presumed proteins affect gloves in a similar way, regardless of the nature, and source, of the protein. This would require a greater study to understand if this is the case. If it is found that proteins have similar reactions across different glove

materials. This means that one protein could be used to assess the friction modification of gloves in industrial assessment practices.

- The work conducted in this chapter has shown a suitable match for NRL by using a combination of sugars and flour. Although, this is only significantly similar at the 1 N load only. However, with the NBR a match was found using a formulation of diluted sugars. This was significantly similar across all loads used in this study. It was hoped that the development would yield a synthetic material which matches the frictional properties of both NRL and NBR, however this is not the case. It could be that further materials match the frictional properties of both glove materials, but this would require further investigation.
- As the industry is aiming more focus at the NBR material, a solution had been created which provides a suitable alternative to using blood tissues to assess frictional changes. This study has therefore proved a suitable alternative for friction analysis for NBR without the use of animal models, negating any storage issues, biohazardous waste disposal, or ethical concerns.
- Where this work validates synthetic models to assess blood friction, the inherent differences in blood nature and behaviour must be considered for other studies. This work shows that the models can be used to assess how blood modifies friction immediately after contamination whilst still wet, but not after the blood has become tacky or dried onto the gloves, which will occur in some cases.

Chapter Ten: Conclusions and future work

Three areas have been explored in this thesis in order to further advance the understanding of glove assessments and their effects on glove users. The first is the assessment of the ease of donning and doffing different glove materials in realistic conditions (172, 173), followed by understanding how the key chemical and physical parameters of the glove polymers affect user performance. Finally, an understanding of the key differences between glove materials when contaminated, and how this impacts the performance of the glove users (232). By assessing these key areas, the whole thesis has taken the innovative approach of looking at tying together the chemistry, mechanical, and performance parameters.

10.1 Importance of results for glove assessments

It is clear from the responses of the glove users in Chapter 3 of this thesis that gloves are perceived to have an adverse impact on the user's performance. The impact of these gloves still receives little-to-no assessment at the manufacturing stage. Namely, the gloves are assessed for their main purpose of protection and tested for their barrier properties. However pertinent the barrier integrity is, the findings in this thesis shows that the effects gloves have on users' performance needs to be considered (6).

One of the most common themes noted throughout this thesis is that there is discord, in some areas, between the published literature and industry. It would appear, through the continued marketing of gloves aimed at improving tactility, grip, and dexterity, that the manufacturers are aware of the common issues noted from glove users (69, 75, 95). However, it is unclear what investigations glove manufacturers are performing to evaluate, and ultimately alleviate these issues in-house. From the manufacturer's perspective, understanding how the behaviour of these gloves are modified through their daily use, and how the gloves affect user performance, will allow the modification of properties to maximise the performance of glove users. Manufacturers do not publish the criticisms on their products, as this allows them to improve and lead the industry with novel technologies. However, this leaves collaboration on projects of this ilk problematic. More transparency with the issues known by the manufacturing companies would lead to more targeted assessments, which would lead to greater user satisfaction if perceived issues can be corrected. Whilst it is appreciated that having an advancement in a technological area is vital for business performance, the privacy around the technologies, and tests conducted within the industries, leaves a vacuum in the literature, especially regarding how glove materials are assessed for their effects on user performance (6).

Key findings

The work conducted in this thesis has shown that the key parameters of stiffness and thickness, as well as the way the material interacts with moisture in the skin, require critical consideration. This is particularly important for the tribological aspects of the glove materials. The key contributions/findings of this thesis are as follows:

- Development of methodology to assess glove donning and investigating correlations to friction/physical properties, in both dry and wet conditions, to understand the behaviour of gloves with different treatments. Including the manufacturing of bespoke gloves and assessing donning performance through defined protocols. Overall, to quickly don, gloves should be stiff, thin, and no moisture should be present.

- Development of synthetic blood surrogates that are easy to create using commercially available constituents. These can be used in lieu of animal blood to assess the differences in tribological properties of gloves and circumvent any safety concerns.

- Established understanding of the glove-contaminant chemical interaction, the tribochemical effects of substances on gloves, and how this affects the performance of glove users (dexterity and sensitivity). The hydrophobicity of the NRL shows a greater decrease in friction, and decreased performance when contaminated. On the other hand, the NBR gloves show little changes in friction. However, some contaminants and surfaces lead to an increase in friction of the NBR gloves. These interactions lead to an increase in performance when NBR gloves are contaminated with mucin. By assessing the changes caused by contaminants, the user performance can be evaluated in more realistic conditions, with measurable differences.

- A key outcome of this thesis shows that comparing gloves between studies, just because they are of the same material, is imprudent. There are clear differences in the dexterity performance of the glove users, which is linked to the polymer chemical constituents, and in turn, their differences in mechanical properties. These mechanical properties have been found to have correlation to their performance, especially in the case of material stiffness. The stiffer materials were found to have lower friction coefficients, and lower performances in dexterity.

The work in this thesis also revealed a gap in knowledge around the sizing of examination gloves. The participants used throughout these studies showed to have either a finger length, or a palm circumference measurement, larger or smaller than the recommended glove size by the Health and Safety Executive (HSE) (149). This would imply that either the gloves are the wrong size for the users, or that the sizing of gloves is not fit for the general population. Further research around this subject has yielded very little, but confusing and contradictory results. Many female healthcare workers cannot find gloves that fit their hands (229), leading to the inference that the sizes used today, are based on archaic anthropometric data based on the hands of males (308). Thus, the HSE makes glove size recommendations which appear to be based on outdated information, leading to erroneous size suggestions. A more accurate sizing scale, with a wider range of glove sizes, which is in accordance with updated anthropometric data, should be created in order to negate the issues arising as a function of loose or tight fitting gloves which would be beneficial to improve user performance, and in some cases, compliance (19).

A summary of the tests conducted in this thesis is shown in Table 10.1, which highlights the principles of the protocols and tests, the outcomes from the tests, and recommendations for improvements in the future. The tests used in this thesis could easily be implemented into glove manufacturing plants, and into the raw material suppliers' labs for newly developed polymers. Some tests however require more refinement in order to save time, such as cutting down the analysis time of the donning tests, or analysing friction at one load, rather than a range.

Table 10.1. Summary of methodologies and assessments used in this thesis along with the key findings and recommendations for future work.

Chapter	Assessment conducted	Developed protocols	Findings/Novelty of Research	Recommendations for Improvement and future use	Limitations
4 & 5	**Donning and doffing of gloves in wet and dry conditions**	Method of measuring the time taken for gloves to be donned and doffed and identifying the key stages of donning.	Three key stages to donning are affected by the presence of moisture. Doffing unaffected by material or moisture presence. Correlations found between the glove donning time and stiffness, with the thicker gloves taking longer to don. NBR gloves treated with 1000-2000 ppm are quicker to don, as well as polymer coated NRL.	Addition of sweat, rather than water could highlight further differences in the donning process	Assessing the key stages of donning is time consuming. Can be circumvented by assessing the time taken to don gloves as a whole, rather than assessing stages.
4, 5, & 6	**Fit of gloves to the hand**	Existing measurement methods	Discrepancies between glove sizes, glove former sizes, and general hand size, leading to issues with fit.	A data bank of glove size and fit to more recent anthropometric data could further highlight discrepancies.	
4 & 5	**Glove-skin friction with AMTI force plate**	Assessment methodology of skin and material friction as well as the bulk behaviour of material under load.	NBR gloves treated with 1000-2000 ppm produce the least friction, as were the polymer coated NRL gloves in the wet condition. Bulk behaviour of the material changes depending on thickness. Thicker gloves rolled more, whilst the thinner gloves caused more skin adhesion to the glove.	Protocol could be useful with just one or two materials and using only one specified load. Securing at the side of the plate can help assess material behaviour under load.	Time consuming for multiple gloves and conditions with multiple participants

6	**Outer material friction with AMTI force plate and tools.**	Repeatable and easy assessment methodology of gloves with tools. Understanding of material behaviour on tool patterns.	The stiffer the glove, the lower the friction coefficients were.	Using more participants with different glove sizes to fully understand how loose/tight fitting gloves would change the tribology, and in turn could affect dexterity/sensitivity.	To assess the friction coefficients accurately across multiple gloves and surfaces is time consuming.
7, 8 & 9	**Contamination friction with AMTI force plate and tools. Application of the contaminant to the gloves and monitoring of evaporation.**	Friction protocol that can aid the Understanding of the effects of different contaminants on gloves.	Affinity of the contaminant affects the tribological behaviour of the glove materials. NRL shows a greater reduction in friction when contaminated, and has a generally low surface wettability NBR shows a reduced friction with most of the contaminants, however the decrease is not great, and generally has a high surface wettability. Development of a synthetic blood which can be used in place of whole blood to assess frictional differences with gloves.	More work needs to be conducted on the effects of blood in the various stages of drying. Further exploration of a synthetic blood which can be used on both NRL and NBR gloves to replicate the frictional effects of blood. Further analysis of blood in different drying stages is required	Time taken to clean the instrument between contaminant use. Can be improved by sticking to one contaminant, such as blood (or the synthetic version created in chapter 9). Different synthetic bloods needed for each glove type.
6	**Dexterity: Pegboard**	Existing test methods	Comparing gloves of the same material is imprudent without chemical knowledge. Gloves of the same core material have different physical properties based on the chemical additives and physical parameters. The assembly test shows greater differences, thus may be more useful for assessing finer differences. Correlation between performance and stiffness as stiffer gloves restrict movement.	Will be useful for determining effects of newer gloves with different grip patterns/thicknesses when correlated to the mechanical and tribological performance.	

8	**Dexterity: contaminated pegboard and CSPDT**	Application of mucin contaminant to gloves and assessing both dexterity and sensitivity through defined protocols . Novel to assessing dexterity with medical gloves.	Fine dexterity is increased due to the film formation effects of mucin. Clear differences in glove behaviour can be distinguished. NRL performs worse than NBR when contaminated. Reduction in friction with the NRL adversely affects the gross dexterity and sensitivity of NRL glove users.	Needs to be used with a greater variety of contaminants with different properties to fully understand the effects different contaminants may have. Using different tests, where varied tasks and different tools are required, could highlight further differences between materials and the effects of different contaminants. Assessments that require greater interaction with the environment would be more simulative of tasks conducted when gloves are worn.	Time taken to clean between tests is a limitation, especially when multiple conditions are studied. This could be minimised by changing the assessment to assess contamination on the equipment in the first instance, rather than the gloves.
8	**Sensitivity: contaminated simulated medical tactile test (bumps)**	Protocol developed to apply contaminants and repeatable measures of sensitivity. Novel to assessing sensitivity with medical gloves.	NRL provides greater sensitivity than the NBR glove. NBR shows improved sensitivity when contaminated. NRL shows a decrease in sensitivity when contaminated. Useful method for determination of dampened sensitivity from placing gloves over the fingers.	Re-print test bed to remove defects on board. Conduct with a greater variety of contaminants. Further tests could be developed to measure the impact of contaminants, such as measuring vibration transmission.	Requires a wider bumps range, also some other discrimination on the test (such as purposely manufactured grooves) to help with differentiating differences between gloves and conditions.

10.2 Effects of glove properties

A summary of the gloves' properties, and their effects on the user/performance are shown in Figure 10.1. The figure highlights the effects of each of the properties analysed in this thesis if the property is increased. For example, in the case of the wettability of the glove materials, an increase in the surface wettability property leads to an increase in friction and chemical interaction over the less wettable surface. The increase in both of these behaviours, leads to an increase in dexterity and sensitivity. The positive icons indicate an increase, whilst the negative indicates a decrease. In each case, these can be reversed to obtain an opposite effect.

Caveats do exist however, for example as the size decreases, this still has a negative effect on the glove fit, as it will be too small, which will incur restricted movement and greater effects on dexterity. Ideally, a glove should be of a low stiffness, with a good surface wettability with a good fit. This produces gloves which are easy to don and increases dexterity and sensitivity performance of users when compared other gloves. Of the parameters addressed, the most affected is the dexterity of the glove users. By changing the material properties studied in this thesis, at the manufacturing stage, improvements could be made on the performance of the gloves, as noted in the donning in Chapter 5 where different thicknesses and chemical treatment strengths were analysed. In some cases, the material parameters are intrinsically affected by one another, such as the material thickness having an effect on the stiffness. Therefore, adjusting the thickness will impact the stiffness of the gloves, which will, in turn, affect the dexterity and ease of glove donning.

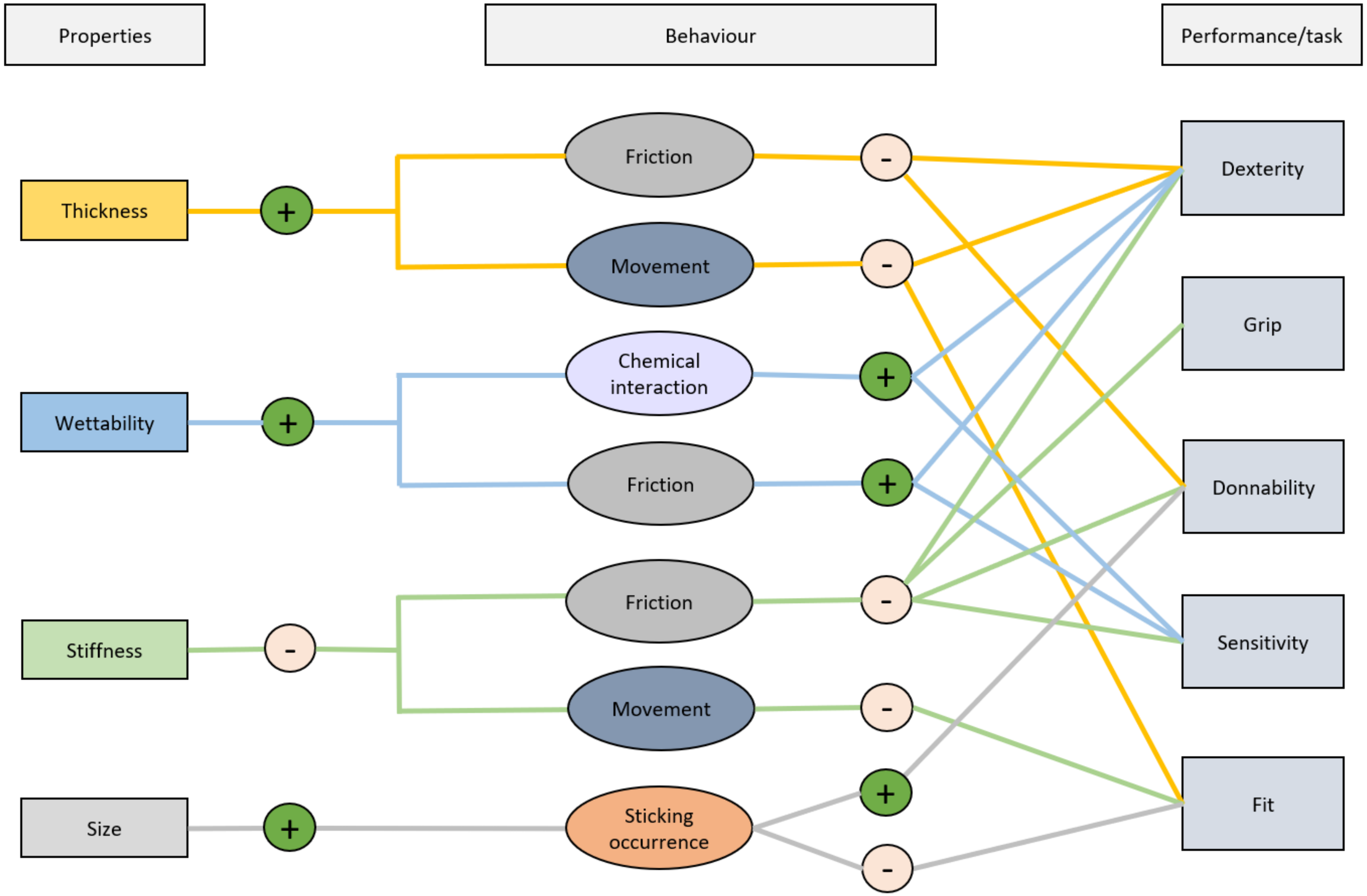


Figure 10.1. Properties assessed in the thesis and how they link to the effects on the gloves and the user performance as the property increases (e.g. thickness gets thicker). '+' indicates an increase, whilst '-' indicates a decrease.

10.3 Recommendations to industry

- The work conducted in this thesis shows that there is a correlation between the stiffness of the gloves and the performance parameters (such as dexterity and donning) as well as between tensile strength and performance. It is possible that the correlation between tensile strength and the performance is not a causation, but an indirect correlation as correlations were found between the stiffness and the tensile strength. Further research would need to be carried out to assess this correlation, but the research presents interesting findings, nonetheless. The work conducted suggests that by paying closer attention to these parameters, the performance could be predicted. Stiffer materials were shown to induce a poorer user performance, but reduced friction as the stiffer material is less likely to locally deform.
- For the examination gloves being sold, there are statements of 'increased friction' or 'increased grip', but no information around the effect of contamination of these gloves, or even the tests used to assess the friction, can be ascertained. The work in this thesis has shown that the frictional properties of gloves are modified upon exposure to both powder and liquid contamination. Assessing these contaminant tribological interactions with newer NBR grade gloves will greatly inform of the differences in contaminant interaction, and tribological changes, which are salient to the performance. The use of the synthetic blood developed in Chapter 9 of this thesis would be useful in aiding this understanding.
- Assessing frictional properties in-house when different glove formulations are developed is vital for moving the industry forward. Tribological differences are present between different grades of nitrile materials, which could cause issues with dropping equipment, and more fatigue overtime, as more force is exerted to grip equipment. This is especially pertinent in covid-19 outbreaks, in which glove use is becoming more and more frequent, and gloves are worn for tasks which they were previously not worn before.
- When developing gloves with novel polymer coatings, assessing the time taken to don the gloves, in conjunction with the friction measurements would be beneficial, and may show greater differences. In addition, when chlorinating gloves, chlorinating to around 1000ppm appears to be more beneficial to NBR materials. However, when the hands have some moisture present, chlorinating to 2000 ppm shows to be more advantageous. It is possible that an optimum chlorination strength exists in between these two strengths, however the frictional properties should not be the only consideration in the process. The material stiffness, as suggested, plays an important part in the way the gloves move around the fingers, as well as stretch around the hand to ensure an easier donning.

- One of the common comments obtained from the questionnaire in the third Chapter of this thesis was around the fit of gloves. There is a requirement for manufacturers to assess how the sizing grades may affect the donning performance, as it would appear the sizing is based on outdated information and does not apply to the majority of the population. Newer, or even reviewed, sizing could alleviate some of the issues glove users have, as better fitting gloves could remove dexterity and sensitivity issues which users often encounter.

10.4 Future work

The work presented in this thesis brings up some interesting correlations between the physical parameters and the performance of dexterity and donning. Further analysis of these parameters with a larger sample size will provide further confidence in these results. Some of the test procedures, such as the donning methodology created, could be repeated using sweat, rather than just water in order to assess the differences in frictional interactions. Additionally, as the covid-19 pandemic is very much prevalent, and regular hand-washing is encouraged, a larger range of skin care products are likely to be present on hands prior to donning gloves (178). These products are namely moisturisers used due to frequent hand washing, which will provide more moisture to the skin. As well as an increase in moisturisers, hand cleaning products are also more frequently used. Under current guidelines, these are 70% (minimum) alcohol based hand sanitisers (309), which will dry the skin out, reducing the moisture to abnormal levels. Assessing how these materials and coatings interact with these products would further advance the knowledge of how the different coatings affect donning and doffing in different hand conditions.

As covid-19 forces industries to use more PPE, particularly gloves, there is a likelihood more issues will arise as a result of an increase of both more frequent use, and more frequent users (30). This does not pertain solely to the medical field. As stated in the introduction to this thesis, medical gloves are worn in a myriad of fields, and are used for many more applications. Gloves will now be worn for situations where they were not required previously, highlighting further issues. Ascertaining greater information regarding how gloves may affect performance in other fields will increase the knowledge of how to incorporate more standard tests, more contaminants that gloves are exposed to, and understand the material parameters which may affect the performance in different areas. Therefore, it would be interesting to carry out another study based on the views of glove users to widen the particular issues of interest.

A few caveats exist in the studies conducted in the thesis, such as the correlation of parameters to the strain once the glove is on the hand. Measuring strain when the glove is on the hand has not been previously carried out. Using instrumentation such as digital image correlation would advance the knowledge in this area. Knowing the strain that a glove undergoes and assessing how that strain affects dexterity and sensitivity, could be vital for performance measuring. This ties in very closely for the requirement to assess the general sizing of medical examination gloves.

One of the issues highlighted by glove manufacturers was with getting polymer coatings to bind to the NBR material. This knowledge is missed in the literature but is known by the glove manufacturers, which would explain some of the differences in results between studies assessing these coatings. Studies oriented at these technologies will allow greater understanding of what is happening at the skin-glove material interface, allowing insight for further technological advancements to help with glove donning.

Many of the contaminants used in this thesis are of both a polar and non-polar nature, meaning their interactions will be difference based upon exposure to different glove materials. However, the interaction, although based on a lot of information regarding the chemistry of the materials and contaminants, does need further work for confirmation of key interactions. Knowing what the gloves are composed of, in full, is key to understanding this. X-ray diffraction is a useful tool for targeted analysis of what may be present on the surface of the glove materials, which will allow for greater understanding of the surface chemistry. By understanding this on a molecular level, the interaction with the contaminants can then be understood, and the surface chemistry could be modified to increase or decrease the tribological interactions with different surfaces. Additionally, more analytical chemistry techniques could be used to assess how contaminants are affecting gloves on a chemical level, such as mass spectrometry to assess if contaminants are present on the gloves through simple adhesion, or if there are chemical interactions.

Tying together the physical and chemical interactions gloves have with their environment is paramount to identifying how gloves are affecting both user perception and performance. Only by assessing the gloves in the conditions they are used in can the effects of gloves be identified. Future tests should be considering the impacts gloves have on users once they are contaminated, rather than just assessing in dry, unrealistic conditions. Ultimately, by making the tests more representative of the environments gloves are used in, this thesis shows that sensitivity, dexterity, friction, and the donning efficiency of gloves are affected by contamination (172, 173, 232). It is hoped that the methodology developed and implemented in this thesis, along with the advancement in knowledge of the chemical interactions and friction differences, can lead the industry to a better understanding of how medical examination gloves affect user performance.

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Appendices

Appendix A – Publications

Publications

- **PREECE, D**, LEWIS, R and CARRÉ, MJ. Efficiency of Donning and Doffing Medical Examination Gloves. International Journal of Ergonomics [online]. 2020. Vol. 10, no. 1, p. 1–17.
- **PREECE, D,** LEWIS, R and CARRÉ, MJ. A critical review of the assessment of medical gloves. Tribology - Materials, Surfaces & Interfaces [online]. 2020. P. 1–10. DOI 10.1080/17515831.2020.1730619.
- **PREECE, D**, LEWIS, R and CARRÉ, MJ. Effects of Mucin on the dexterity and tactile sensitivity of medical glove users. Biotribology [online]. 2020. Vol. 24, 100146. DOI 10.1016/j.biotri.2020.100146.
- **PREECE, D**, HONG, T, TONG, HK, LEWIS, R and CARRÉ, MJ. The effects of chlorination, thickness, and moisture on glove donning efficiency. Ergonomics [online]. 2021. P. 1-12 DOI 10.1080/00140139.2021.1907452.

  WATSON, M, CHRISTOFOROU, P, HERRERA, P, **PREECE, D,** CARRELL, J, HARMON, M, KRIER, P, LEWIS, S, MAITI, R, SKIPPER, W, TAYLOR, E, WALSH, J, ZALZALAH, M, ALHADEFF, L, KEMPKA, R, LANIGAN, J, LEE, ZS, WHITE, B, ISHIZAKA, K, LEWIS, R, SLATTER, T, DWYER-JOYCE, R and MARSHALL, M. An analysis of the quality of experimental design and reliability of results in tribology research. Wear [online]. April 2019. Vol. 426–427, p. 1712–1718. DOI 10.1016/j.wear.2018.12.028.

Conferences

- **PREECE, D,** LEWIS, R and CARRÉ, MJ. A review of the assessment of medical gloves. Poster presented at: Tribomotion: Where performance and motion meet friction. *44th Leeds Lyon Symposium on Tribology*. 4th-6th September 2017; Lyon, France.
- **PREECE, D,** LEWIS, R and CARRÉ, MJ. A review of the assessment of medical gloves. Poster presented at: Tribology in motion. *TriboUK 2017*. 27th-28th April 2017; London, UK.
- **PREECE, D,** LEWIS, R and CARRÉ, MJ. The Effects of Mucin on Medical Glove Users and Dexterity and Tactile Sensitivity. Poster presented at: The Impact of Tribology in the Modern World. *TriboUK 2018*. 12th-13th April 2018; Sheffield, UK.
- **PREECE, D,** LEWIS, R and CARRÉ, MJ. Effects of mucin on medical glove tribology and performance. Oral presentation at: Tribology in daily life. *46th Leeds Lyon Symposium on Tribology*. 4th-6th September 2019; Lyon, France.

Appendix B – Supplementary data for Chapter Four

B1. Total donning times for each step with paired t-test results for total time taken between dry and wet conditions (n=14).

Glove/Condition		Preparation	Hand Insertion	Manipulation	Total donning time	t-test
		Average times taken for each step (s)				
Cl NBR	Dry	1.21 (±0.71)	1.95 (±0.93)	0.83 (±0.54)	3.99 (±1.18)	*t(13)=-3.183 p=.007**
	Wet	1.48 (±0.99)	3.88 (±.2.13)	1.14 (±0.98)	6.50 (±3.34)	
PC NBR	Dry	1.53 (±1.43)	2.33 (±1.06)	0.97 (±0.77)	4.83 (±2.74)	*t(13)=-2.901 p=.012**
	Wet	1.67 (±0.85)	4.84 (±3.10)	1.08 (±0.63)	7.59 (±4.35)	
Cl NRL	Dry	1.14 (±0.71)	1.94 (±0.91)	1.2 (±0.92)	4.28 (±1.47)	*t(13)=-3.125 p=.008**
	Wet	1.21 (±0.63)	4.63 (±3.24)	1.07 (±0.98)	6.91 (±4.13)	
PC NRL	Dry	0.95 (±0.54)	2.13 (±1.07)	0.92 (±0.75)	4.00 (±1.71)	*t(13)=-1.646 p=.124*
	Wet	0.99 (±0.63)	3.06 (±1.47)	0.78 (±0.51)	4.83 (±1.70)	

*± denotes standard deviation, * Indicates statistical significance (p<.05)*

B2. Time taken for participants to doff gloves, with paired t-tests comparing dry and wet conditions.

Glove/Condition		**Time taken (s)**	**t-test**
Cl NBR	Dry	1.68 (±0.45)	*t(13)=-0.587 p=.562*
	Wet	1.80 (±0.80)	
PC NBR	Dry	1.93 (±0.29)	*t(13)=-0.090 p=.407*
	Wet	1.84 (±0.65)	
Cl NRL	Dry	1.80 (±0.41)	*t(13)=-0.089 p=.928*
	Wet	1.80 (±0.46)	
PC NRL	Dry	1.63 (±0.55)	*t(13)=-0.765 p=.452*
	Wet	1.78 (±0.42)	

± denotes standard deviation.

B3. Friction coefficients for each participant in each condition

	Chlorinated NBR							
	Participant							
	1		2		3		4	
Condition	Load (N)	µ	Load (N)	µ	Load (N)	µ	Load (N)	µ
Dry	0.09	3.04	0.10	3.63	0.10	3.79	0.10	3.55
	0.22	2.55	0.23	2.60	0.21	2.52	0.24	2.16
	0.57	1.27	0.57	1.73	0.50	1.55	0.33	2.28
	0.71	1.49	0.80	1.74	0.83	1.56	0.77	1.85
	1.04	1.10	0.98	1.68	1.03	1.19	1.04	1.44
Wet	0.14	2.26	0.17	4.09	0.11	4.42	0.15	4.80
	0.30	1.85	0.39	2.17	0.26	2.96	0.30	2.67
	0.39	1.70	0.42	2.20	0.35	2.47	0.44	2.35
	0.80	1.28	0.87	1.32	0.84	1.33	0.85	1.87
	1.13	1.39	0.93	1.87	1.04	1.52	1.03	1.62
	Polymer Coated NBR							
	Participant							
	1		2		3		4	
Condition	Load (N)	µ	Load (N)	µ	Load (N)	µ	Load (N)	µ
Dry	0.11	2.73	0.12	4.51	0.11	3.71	0.13	3.52
	0.36	1.93	0.3	2.05	0.28	2.85	0.32	1.97
	0.41	1.72	0.4	2.18	0.33	2.74	0.39	2.11
	0.82	1.58	0.77	2.15	0.70	1.57	0.79	1.73
	0.95	1.01	0.94	2.06	0.94	1.67	1.04	1.57
Wet	0.10	5.17	0.12	6.73	0.10	6.50	0.09	8.81
	0.29	3.50	0.29	3.67	0.28	4.38	0.23	5.60
	0.37	3.00	0.36	3.18	0.34	3.95	0.34	4.22
	0.76	2.03	0.79	2.62	0.63	2.27	0.78	1.76
	1.08	1.68	1.01	1.88	1.02	1.47	1.09	1.69
	Chlorinated NRL							
	Participant							
	1		2		3		4	
Condition	Load (N)	µ	Load (N)	µ	Load (N)	µ	Load (N)	µ
Dry	0.12	1.93	0.11	3.44	0.13	2.65	0.11	5.39
	0.30	1.34	0.20	3.36	0.25	2.75	0.27	1.66
	0.48	1.20	0.39	2.19	0.43	2.07	0.37	1.15
	0.79	1.08	0.89	1.93	0.79	2.08	0.76	1.29
	1.04	1.11	0.90	1.65	1.06	1.52	0.88	1.39
Wet	0.10	1.99	0.08	4.86	0.11	4.27	0.10	4.86
	0.28	2.07	0.35	2.19	0.27	4.78	0.38	2.23
	0.38	1.86	0.51	2.52	0.48	3.44	0.48	2.18
	0.80	1.56	0.73	2.20	0.80	2.12	0.72	2.31
	1.05	1.49	0.89	2.11	1.03	2.21	1.09	2.26

	Polymer Coated NRL							
	Participant							
	1		2		3		4	
Condition	Load (N)	μ	Load (N)	μ	Load (N)	μ	Load (N)	μ
Dry	0.10	1.18	0.09	2.66	0.12	1.26	0.13	1.21
	0.25	1.32	0.22	1.86	0.21	2.25	0.25	1.82
	0.44	1.26	0.42	1.67	0.39	1.85	0.45	1.79
	0.74	1.24	0.74	2.00	0.78	1.61	0.73	1.81
	1.03	1.03	0.96	1.54	1.02	1.48	0.96	1.61
Wet	0.13	1.71	0.09	2.81	0.11	2.29	0.12	2.64
	0.28	2.05	0.28	2.19	0.31	1.78	0.29	1.99
	0.34	2.05	0.44	1.80	0.37	1.75	0.34	1.48
	0.81	1.83	0.72	1.83	0.8	1.40	0.73	1.54
	1.04	1.9	0.89	1.90	1.02	1.56	0.99	1.84

B4. Paired t-tests of friction between wet and dry conditions of NBR gloves

		Participant			
Condition	Load	1	2	3	4
Polymer coated	0.1	*t(2)=8.437 p=.047**	*t(2)=6.867 p=.037**	*t(2)=4.706 p=.032**	*t(2)=5.243 p=.014**
	0.25	*t(2)=0.990 p=.124*	*t(2)=1.520 p=.523*	*t(2)=2.452 p=.138*	*t(2)=10.267 p=.659*
	0.5	*t(2)=0.273 p=.158*	*t(2)=-5.620 p=.034**	*t(2)=1.606 p=.514*	*t(2)=1.797 p=.648*
	0.75	*t(2)=4.634 p=.478*	*t(2)=1.175 p=.134*	*t(2)=2.645 p=.184*	*t(2)=0.407 p=.325*
	1	*t(2)-3.077 p=.156*	*t(2)=-0.678 p=.189*	*t(2)=-1.372 p=.844*	*t(2)=0.725 p=.072*
Chlorinated	0.1	*t(2)=2.051 p=.103*	*t(2)=-1.681 p=.960*	*t(2)=-8.630 p=.020**	*t(2)=-7.278 p=.014**
	0.25	*t(2)=3.942 p=.272*	*t(2)=-1.633 p=.008**	*t(2)=-4.301 p=.006**	*t(2)=-0.644 p=.238*
	0.5	*t(2)=-5.399 p=.001**	*t(2)=-1.300 p=.695*	*t(2)=-5.008 p=.313*	*t(2)=0.930 p=.164*
	0.75	*t(2)=-4.704 p=.065*	*t(2)=1.899 p=.641*	*t(2)=2.740 p=.028**	*t(2)=-0.046 p=.183*
	1	*t(2)=-2.133 p=.046**	*t(2)=-2.133 p=.295*	*t(2)=-2.119 p=.053*	*t(2)=-1.284 p=.218*

**Denotes statistical significance (p<.05)*

B5. Paired t-tests of friction between wet and dry conditions of NRL gloves

		Participant			
Condition	Load	1	2	3	4
Polymer coated	0.1	*t(2)=-1.856 p=.241*	*t(2)=-2.78 p=.007*	*t(2)= -2.794 p=.157*	*t(2)=4.117 p=.016**
	0.25	*t(2)=-2.283 p=.144*	*t(2)=-1.418 p=.342*	*t(2)=-0.523 p=.634*	*t(2)=-0.198 p=.847*
	0.5	*t(2)=-3.373 p=.165*	*t(2)=0.474 p=.720*	*t(2)=3.559 p=.890*	*t(2)=1.327 p=.323*
	0.75	*t(2)= 1.319 p=.436*	*t(2)=-0.455 p=.536*	*t(2)=0.778 p=.404*	*t(2)=0.763 p=.524*
	1	*t(2)= -3.526 p=.128*	*t(2)=-1.065 p=.352*	*t(2)=-0.682 p=.623*	*t(2)=-0.992 p=.440*
Chlorinated	0.1	*t(2)=1.445 p=.080*	*t(2)=3.443 p=.121*	*t(2)=-10.030 p=.002**	*t(2)=-1.227 p=.252*
	0.25	*t(2)=16.978 p=.005**	*t(2)=-3.383 p=.067*	*t(2)=-2.594 p=.206*	*t(2)=-0.442 p=.777*
	0.5	*t(2)= 14.599 p=.054*	*t(2)=1.278 p=.109*	*t(2)=0.0569 p=.250*	*t(2)=4.515 p=.049*
	0.75	*t(2)=13.631 p=.002**	*t(2)= 1.460 p=.198*	*t(2)=-0.96 p=.808*	*t(2)=7.695 p=.023**
	1	*t(2)=23.100 p=.014**	*t(2)=44.530 p=<.001**	*t(2)=-4.343 p=.081*	*t(2)=4.762 p=.036**

**Denotes statistical significance (p<.05)*

Appendix C – Supplementary data for Chapter Five

C1. Statistics for differences in donning time regarding thickness (Section 5.4.5)

C1.1. One-Way ANOVA analysis of the donning time of a single glove in dry and wet conditions.

Condition	*p*-value	
	Thin	Thick
Dry	*F(3, 44)=2.464* *p=.075*	*F(3, 44)= 2.329* *p=.087*
Wet	*F(3, 44)=1.754* *p=.170*	*F(3, 44)=2.845* *p=.048**

**Denotes statistical significance (p<.05).*

C1.2. Tukey HSD analysis donning time of the thick gloves in wet condition (ANOVA =F(3, 44)=2.845 *p*=.048).

Pair	*Q-stat*	*p*-value
E vs F	*1.996*	*.500*
E vs G	*0.859*	*.900*
E vs H	*3.902*	*.040**
F vs G	*1.137*	*.835*
F vs H	*1.906*	*.534*
G vs H	*3.043*	*.153*

**Denotes statistical significance (p<.05).*

C1.3. Kruskal-Wallis of thin and thick gloves in dry and wet conditions from the preparation stage of donning.

Condition	Results	
	Thin	Thick
Dry	*H(3, 44)=1.325* *p=.222*	*H(3, 44)=1.200* *p=.753*
Wet	*H(3, 44)=0.876* *p=.831*	*H(3, 44)=4.260* *p=.235*

C1.4. Kruskal-Wallis of thin and thick gloves in dry and wet conditions from the hand insertion stage of donning.

Condition	Results	
	Thin	Thick
Dry	*H(3, 44)=3.650* *p=.302*	*H(3, 44)=2.641* *p=.133*
Wet	*H(3, 44)=2.746* *p=.433*	*H(3, 44)=8.736* *p=.019**

**Denotes statistical significance (p<.05).*

C1.5. Kruskal-Wallis of thin and thick gloves in dry and wet conditions from the manipulation of donning.

Condition	Results	
	Thin	Thick
Dry	*H(3, 44)=1.486 p=.686*	*H(3, 44)=2.852 p=.415*
Wet	*H(3, 44)=2.328 p=.507*	*H(3, 44)=0.723 p=.868*

C1.6. P-values of Post-Hoc Dunn test of thick gloves in the wet condition from the hand insertion stage of donning.

Glove sample	***p-value***		
	E	F	G
F	*Z=1.506 p=.066*		
G	*Z=-0.619 p=.268*	*Z=0.085 p=.466*	
H	*Z=2.878 p=.002**	*Z=0.769 p=.221*	*Z=1.635 p=.051*

**Denotes statistical significance (p<.05).*

C1.7. t-test results comparing thin and thick gloves in dry and wet conditions.

Glove Sample	Results	
	Dry	Wet
500ppm	*t(11)=-1.140 p=.115*	*t(11)=-1.842 p=.630*
1000ppm	*t(11)=-2.823 p=.008**	*t(11)=-1.440 p=.828*
1500ppm	*t(11)=-0.698 p=.503*	*t(11)=-0.848 p=.252*
Control	*t(11)=0.116 p=.897*	*t(11)=-0.904 p=.350*

**Denotes statistical significance (p<.05).*

C2. Friction coefficients for participants 1-3

C2.1. CoF of wet and dry for participant 1

Glove Sample	Condition	Load (N)		
		Low	Medium	High
A	Dry	2.80 (±0.05)	1.89 (±0.01)	1.98 (±0.01)
	Wet	5.44 (±0.27)	2.17 (±0.02)	1.98 (±0.01)
B	Dry	1.58 (±0.04)	2.56 (±0.02)	2.09 (±0.04)
	Wet	1.88 (±0.03)	2.11 (±0.02)	1.82 (±0.05)
C	Dry	2.49 (±0.07)	2.64 (±0.01)	2.44 (±0.01)
	Wet	3.39 (±0.01)	1.96 (±0.05)	1.84 (±0.01)
D	Dry	5.65 (±0.17)	3.07 (±0.03)	2.69 (±0.01)
	Wet	6.78 (±0.01)	3.75 (±0.21)	1.99 (±0.03)
E	Dry	2.66 (±0.01)	2.18 (±0.04)	1.95 (±0.01)
	Wet	6.40 (±0.24)	2.68 (±0.04)	2.98 (±0.03)
F	Dry	2.80 (±0.05)	2.15 (±0.01)	1.89 (±0.01)
	Wet	3.15 (±0.01)	2.85 (±0.01)	2.65 (±0.01)
G	Dry	2.02 (±0.07)	1.52 (±0.01)	1.38 (±0.01)
	Wet	6.81 (±0.43)	2.77 (±0.04)	1.82 (±0.03)
H	Dry	2.11 (±0.06)	1.82 (±0.01)	1.67 (±0.01)
	Wet	1.40 (±0.32)	2.45 (±0.03)	1.79 (±0.03)

C2.2. CoF of wet and dry for participant 2

Glove Sample	Condition	Load (N)		
		Low	Medium	High
A	Dry	5.06 (±0.19)	2.66 (±0.04)	2.17 (±0.03)
	Wet	6.55 (±0.71)	2.62 (±0.01)	2.76 (±0.02)
B	Dry	2.36 (±0.07)	1.83 (±0.01)	1.63 (±0.02)
	Wet	2.64 (±0.01)	2.10 (±0.01)	2.07 (±0.01)
C	Dry	3.32 (±0.14)	2.14 (±0.08)	1.91 (±0.01)
	Wet	4.88 (±0.05)	3.37 (±0.04)	3.08 (±0.02)
D	Dry	4.78 (±0.06)	3.94 (±0.02)	4.44 (±0.07)
	Wet	5.63 (±0.33)	3.63 (±0.04)	3.16 (±0.02)
E	Dry	7.33 (±0.40)	3.19 (±0.18)	2.13 (±0.06)
	Wet	10.43 (±0.40)	3.70 (±0.12)	2.55 (±0.04)
F	Dry	3.43 (±0.07)	2.17 (±0.01)	1.78 (±0.02)
	Wet	4.77 (±1.13)	2.44 (±0.08)	3.38 (±0.03)
G	Dry	4.84 (±0.29)	1.87 (±0.06)	1.34 (±0.06)
	Wet	10.76 (±1.18)	3.48 (±0.10)	2.34 (±0.13)
H	Dry	2.96 (±0.02)	2.17 (±0.03)	1.91 (±0.01)
	Wet	2.81 (±0.02)	2.56 (±0.01)	2.41 (±0.04)

C2.3. CoF of wet and dry for participant 3

Glove Sample	Condition	Load (N)		
		Low	Medium	High
A	Dry	3.18 (±0.21)	1.33 (±0.01)	1.68 (±0.02)
	Wet	3.06 (±0.06)	2.23 (±0.02)	2.08 (±0.01)
B	Dry	1.85 (±0.22)	1.97 (±0.01)	1.58 (±0.01)
	Wet	3.58 (±0.27)	2.89 (±0.02)	1.85 (±0.01)
C	Dry	1.12 (±0.22)	0.46 (±0.01)	1.29 (±0.17)
	Wet	3.15 (±0.13)	2.88 (±0.03)	2.34 (±0.01)
D	Dry	3.76 (±0.23)	0.93 (±0.03)	0.62 (±0.06)
	Wet	4.15 (±0.17)	2.19 (±0.12)	1.58 (±0.03)
E	Dry	2.93 (±0.02)	2.45 (±0.19)	1.91 (±0.08)
	Wet	5.16 (±0.13)	2.34 (±0.01)	2.29 (±0.01)
F	Dry	4.78 (±0.08)	2.22 (±0.04)	1.40 (±0.03)
	Wet	4.02 (±0.01)	2.03 (±0.02)	2.14 (±0.11)
G	Dry	3.44 (±0.88)	0.93 (±0.01)	1.35 (±0.13)
	Wet	4.61 (±0.10)	3.36 (±0.05)	2.28 (±0.12)
H	Dry	1.22 (±0.01)	1.62 (±0.05)	2.08 (±0.02)
	Wet	1.29 (±0.35)	2.91 (±0.01)	2.40 (±0.17)

C3. Data and statistical tests for friction regarding participant 1 (Section 5.4.6)

C3.1. ANOVA tests conducted on friction results from Participant 1 investigating for differences in results across all conditions

	Thin		Thick	
Load	Dry	Wet	Dry	Wet
Low	*F(3,8)=976.320 p=<.001**	*F(3,8)=756.732 p=<.001**	*F(3,8)=176.097 p=<.001**	*F(3,8)=241.911 p=<.001**
Medium	*F(3,8)=2482.993 p=<.001**	*F(3,8)=174.823 p=<.001**	*F(3,8)=530.352 p=<.001**	*F(3,8)=88.559 p=<.001**
High	*F(3,8)=595.879 p=<.001**	*F(3,8)=30.076 p=<.001**	*F(3,8)=379.920 p=<.001**	*F(3,8)=1551.714 p=<.001**

** Denotes statistical signifnicance (p<.05)*

C3.2. Tukey's HSD test conducted on thin and thick gloves in dry and wet conditions from Participant 1.

		Dynamic Dry			Dynamic Wet		
Load (N)	**Glove Sample**	A	B	C	A	B	C
0.1	B	*Q= 21.711 p=.001**			*Q= 45.155 p=.001**		
	C	*Q=5.492 p=.020**	*Q=16.219 p=.001**		*Q=25.959 p=.001**	*Q=19.196 p=.001**	
	D	*Q=50.641 p=.001**	*Q= 72.352 p=.001**	*Q= 53.133 p=.001**	*Q=17.007 p=.001**	*Q=62.162 p=.001**	*Q=42.966 p=.001**
0.5	B	*Q=68.380 p=.001**			*Q=0.936 p=.900*		
	C	*Q= 76.908 p=.001**	*Q=8.528 p=.001**		*Q=3.362 p=.159*	*Q=2.426 p=.377*	
	D	*Q=120.490 p=.001**	*Q=52.110 p=.001**	*Q=43.582 p=.001**	*Q=24.859 p=.001**	*Q=25.796 p=.001**	*Q=28.221 p=.001**
1	B	*Q=7.670 p=.003**			*Q=9.661 p=.001**		
	C	*Q=34.373 p=.001**	*Q=26.703 p=.001**		*Q=8.689 p=.001**	*Q=0.972 p=.896*	
	D	*Q=25.942 p=.001**	*Q= 45.272 p=.001**	*Q=18.569 p=.001**	*Q=0.580 p=.900*	*Q=10.241 p=.001**	*Q=9.269 p=.001**
Load (N)	**Glove Sample**	E	F	G	E	F	G
0.1	F	*Q=4.791 p=.039**			*Q=19.395 p=.001**		
	G	*Q=21.715 p=.001**	*Q=26.505 p=.001**		*Q=2.424 p=.378*	*Q=21.818 p=.001**	
	H	*Q=18.771 p=.001**	*Q=23.562 p=.001**	*Q=2.944 p=.238*	*Q=29.871 p=.001**	*Q=10.476 p=.001**	*Q=32.294 p=.001**
0.5	F	*Q=34.088 p=.001**			*Q=8.836 p=.001**		
	G	*Q=30.275 p=.001**	*Q=3.812 p=.102*		*Q=4.771 p=.039**	*Q=4.065 p=.080*	
	H	*Q=13.752 p=.001**	*Q=20.336 p=.001**	*Q=16.523 p=.001**	*Q=12.845 p=.001**	*Q=21.68 p=.001**	*Q=17.616 p=.001**
1	F	*Q=21.651 p=.001**			*Q=21.651 p=.001**		
	G	*Q=76.115 p=.001**	*Q=54.464 p=.001**		*Q=76.115 p=.001**	*Q=54.464 p=.001**	
	H	*Q=78.472 p=.001**	*Q=56.821 p=.001**	*Q=2.357 p=.399*	*Q=78.472 p=.001**	*Q=56.821 p=.001**	*Q=2.357 p=.400*

** Denotes statistical signifnicance (p<.05)*

C3.3. T-tests conducted on participant 1 assessing differences in friction between the thin and thick gloves chlorinated to the same concentration.

	Load	Dynamic	
		Dry	Wet
A-E	Low	*t(2)=-4.457 p=.047**	*t(2)=-3.536 p=.072*
	Medium	*t(2)=11.764 p=.007**	*t(2)=-39.991 p=.879*
	High	*t(2)=-5.741 p=.029**	*t(2)=9.274 p=.033**
B-F	Low	*t(2)=24.497 p=.002**	*t(2)=57.704 p=<.001**
	Medium	*t(2)=-73.674 p=<.001**	*t(2)=41.284 p=.224*
	High	*t(2)=7.143 p=.019**	*t(2)=25.335 p=.002**
C-G	Low	*t(2)=-5.932 p=.027**	*t(2)=13.554 p=.005**
	Medium	*t(2)=-296.052 p=<.001**	*t(2)=-28.273 p=.002**
	High	*t(2)=-157.469 p=<.001**	*t(2)=0.760 p=.527*
D-H	Low	*t(2)=-28.301 p=.001**	*t(2)=-29.714 p=.001**
	Medium	*t(2)=-13.996 p=.005**	*t(2)=11.157 p=.008**
	High	*t(2)=29.425 p=.001**	*t(2)=5.676 p=.030**

** Denotes statistical signifnicance (p<.05)*

C3.4. T-tests conducted on participant 1 assessing differences in friction between the dry and wet conditions.

	Dynamic		
Glove Sample	Low Load	Mid Load	High load
A	*t(2)=18.993 p=.003**	*t(2)=20.669 p=.002**	*t(2)=-7.777 p=.016**
B	*t(2)=51.525 p=<.001**	*t(2)=-18.514 p=.003**	*t(2)=-17.843 p=.003**
C	*t(2)=27.000 p=.001**	*t(2)=-27.712 p=.001**	*t(2)=-117.081 p=<.001**
D	*t(2)=11.484 p=.007**	*t(2)=5.643 p=.030**	*t(2)=-34.865 p=.001**
E	*t(2)=27.912 p=.007**	*t(2)=16.842 p=.003**	*t(2)=46.854 p=.001**
F	*t(2)=15.067 p=.004**	*t(2)=113.934 p=.004**	*t(2)=153.871 p=<.001**
G	*t(2)=23.361 p=.004**	*t(2)=47.888 p=<.001**	*t(2)=24.634 p=.002**
H	*t(2)=-4.724 p=.042**	*t(2)=39.733 p=<.001**	*t(2)=7.098 p=.019**

** Denotes statistical signifnicance (p<.05)*

C4. Data and statistical tests for friction regarding participant 2 (Section 5.4.6)

C4.1. ANOVA tests conducted on friction results from Participant 2 investigating for differences in results across all conditions

	Thin		Thick	
Load	Dry	Wet	Dry	Wet
Low	*F(3,8)=41.645 p=<.001**	*F(3,8)=64.916 p=<.001**	*F(3,8)=183.069 p=<.001**	*F(3,8)=68.383 p=<.001**
Medium	*F(3,8)=1229.862 p=<.001**	*F(3,8)=2008.825 p=<.001**	*F(3,8)=112.884 p=<.001**	*F(3,8)=156.675 p=<.001**
High	*F(3,8)=3418.990 p=<.001**	*F(3,8)=2462.809 p=<.001**	*F(3,8)=176.040 p=<.001**	*F(3,8)=137.126 p=<.001**

** Denotes statistical signifnicance (p<.05)*

C4.2. Tukey's HSD test conducted on thin and thick gloves in dry and wet conditions from Participant 2.

		Dry			Wet		
Load (N)	**Glove Sample**	A	B	C	A	B	C
0.1	B	*Q=13.735 p=.001**			*Q=18.79 p=.001**		
	C	*Q=8.854 p=.001**	*Q=4.882 p=.035**		*Q=8.090 p=.002**	*Q=10.789 p=.001**	
	D	*Q=1.422 p=.733*	*Q=12.313 p=.001**	*Q=7.432 p=.003**	*Q=4.468 p=.053*	*Q=14.411 p=.001**	*Q=3.622 p=.124*
0.5	B	*Q=32.264 p=.001**			*Q=33.169 p=.001**		
	C	*Q=20.189 p=.001**	*Q=12.076 p=.001**		*Q=48.154 p=.001**	*Q=81.323 p=.001**	
	D	*Q=49.530 p=.001**	*Q=81.794 p=.001**	*Q=69.718 p=.001**	*Q=64.798 p=.001**	*Q=97.697 p=.001**	*Q=16.644 p=.001**
1	B	*Q=24.738 p=.001**			*Q=69.602 p=.001**		
	C	*Q=11.765 p=.001**	*Q=12.973 p=.001**		*Q=31.124 p=.001**	*Q=100.730 p=.001**	
	D	*Q=103.021 p=.001**	*Q=127.760 p=.001**	*Q=114.78 p=.001**	*Q=39.695 p=.001**	*Q=109.300 p=.001**	*Q=8.571 p=.001**
Load (N)	**Glove Sample**	E	F	G	E	F	G
0.1	F	*Q=26.883 p=.001**			*Q=11.678 p=.001**		
	G	*Q=17.141 p=.001**	*Q=9.742 p=.001**		*Q=0.670 p=.900*	*Q=12.349 p=.001**	
	H	*Q=30.112 p=.001**	*Q=3.229 p=.181*	*Q=12.972 p=.001**	*Q=15.709 p=.001**	*Q=4.031 p=.082*	*Q=16.379 p=.001**
0.5	F	*Q=18.685 p=.001**			*Q=24.803 p=.001**		
	G	*Q=24.308 p=.001**	*Q=5.632 p=.017**		*Q=4.411 p=.056*	*Q=20.391 p=.080*	
	H	*Q=18.770 p=.001**	*Q=0.085 p=.900*	*Q=5.539 p=.019**	*Q=22.381 p=.001**	*Q=2.422 p=.378*	*Q=19.969 p=.001**
1	F	*Q=13.736 p=.001**			*Q=20.289 p=.001**		
	G	*Q=31.495 p=.001**	*Q=17.759 p=.001**		*Q=4.915 p=.034**	*Q=25.204 p=.001**	

	H	*Q=8.808 p=.001**	*Q=4.927 p=.034**	*Q=22.686 p=.001**	*Q=3.390 p=.155*	*Q=23.679 p=.001**	*Q=1.521 p=.696*

** Denotes statistical signifnicance (p<.05)*

C4.3. T-tests conducted on participant 2 assessing differences in friction between the thin and thick gloves chlorinated to the same concentration.

	Load	Dynamic	
		Dry	Wet
A-E	Low	*t(2)=6.782 p=.021**	*t(2)=15.110 p=.004**
	Medium	*t(2)=-5.799 p=.029**	*t(2)=-14.241 p=.005**
	High	*t(2)=1.897 p=.198*	*t(2)=-21.918 p=.002**
B-F	Low	*t(2)=13.407 p=.006**	*t(2)=-3.297 p=.081*
	Medium	*t(2)=148.035 p=<.001**	*t(2)=-7.755 p=.016**
	High	*t(2)=-39.222 p=<.001**	*t(2)=86.392 p=<.001**
C-G	Low	*t(2)=6.175 p=.025**	*t(2)=9.010 p=.012**
	Medium	*t(2)=7.674 p=.017**	*t(2)=-3.132 p=.089*
	High	*t(2)=-16.351 p=.004**	*t(2)=-9.568 p=.011**
D-H	Low	*t(2)=-4.842 p=.040**	*t(2)=-102.853 p=<.001**
	Medium	*t(2)=-55.720 p=<.001**	*t(2)=49.795 p=.001**
	High	*t(2)=-73.001 p=<.001**	*t(2)=-77.280 p=<.001**

** Denotes statistical signifnicance (p<.05)*

C4.4. T-tests conducted on participant 2 assessing differences in friction between the dry and wet conditions.

	Dynamic		
Glove Sample	Low Load	Mid Load	High load
A	*t(2)=3.765 p=.064*	*t(2)=-1.582 p=.254*	*t(2)=95.714 p=<.001**
B	*t(2)=5.386 p=.033**	*t(2)=37.738 p=.001**	*t(2)=50.673 p=<.001**
C	*t(2)=25.514 p=.002**	*t(2)=22.431 p=.002**	*t(2)=179.052 p=<.001**
D	*t(2)=2.401 p=.138*	*t(2)=-20.580 p=.002**	*t(2)=-34.379 p=.001**
E	*t(2)=18.172 p=.003**	*t(2)=5.632 p=.030**	*t(2)=21.085 p=.002**
F	*t(2)=2.047 p=.177*	*t(2)=6.599 p=.022**	*t(2)=-67.194 p=<.001**
G	*t(2)=7.281 p=.018**	*t(2)=-44.289 p=.001**	*t(2)=24.042 p=.002**
H	*t(2)=-8.162 p=.013**	*t(2)=25.873 p=.001**	*t(2)=29.958 p=.001**

** Denotes statistical signifnicance (p<.05)*

C5. Data and statistical tests for friction regarding participant 3 (Section 5.4.6)

C5.1. ANOVA tests conducted on friction results from Participant 2 investigating for differences in results across all conditions

	Thin		Thick	
Load	Dry	Wet	Dry	Wet
Low	*F(3,8)=71.470 p=<.001**	*F(3,8)=23.610 p=<.001**	*F(3,8)=33.434 p=<.001**	*F(3,8)=68.383 p=<.001**
Medium	*F(3,8)=581.474 p=<.001**	*F(3,8)=113.568 p=<.001**	*F(3,8)=17.400 p=<.001**	*F(3,8)=156.675 p=<.001**
High	*F(3,8)=14.975 p=.001**	*F(3,8)=712.821 p=<.001**	*F(3,8)=65.387 p=<.001**	*F(3,8)=2.967 p=.092*

** Denotes statistical signifnicance (p<.05)*

C5.2. Tukey's HSD test conducted on thin and thick gloves in dry and wet conditions from Participant 3.

		Dynamic Dry			Dynamic Wet		
Load (N)	Glove Sample	A	B	C	A	B	C
0.1	B	*Q=10.593 p=.001**			*Q=5.096 p=.027**		
	C	*Q=16.394 p=.001**	*Q=2.802 p=.015**		*Q=0.879 p=.900*	*Q=4.217 p=.068*	
	D	*Q=4.692 p= .043**	*Q=15.284 p=.001**	*Q=21.086 p=.001**	*Q=10.632 p=.001**	*Q=5.536 p=.019**	*Q=9.753 p=.001**
0.5	B	*Q=18.638 p=.001**			*Q=18.112 p=.001**		
	C	*Q=26.423 p=.001**	*Q=45.061 p=.001**		*Q=17.686 p=.001**	*Q=0.423 p=.900*	
	D	*Q=12.213 p=.001**	*Q=30.851 p=.001**	*Q=14.210 p=.001**	*Q=1.081 p=.857**	*Q=19.193 p=.001**	*Q=18.768 p=.001**
1	B	*Q=2.013 p=.52*			*Q=18.952 p=.001**		
	C	*Q=7.279 p=.004**	*Q=5.266 p=.024*		*Q=20.929 p=.001**	*Q=39.881 p=.001**	
	D	*Q=19.925 p=.001**	*Q=17.912 p=.001**	*Q=12.646 p=.001**	*Q=41.651 p=.001**	*Q=22.699 p=.001**	*Q=62.579 p=.001**

		Dynamic Dry			Dynamic Wet		
Load (N)	Glove Sample	E	F	G	E	F	G
0.1	F	*Q=1.458 p=.720*			*Q=8.423 p=.001**		
	G	*Q=6.671 p=.007**	*Q=25.212 p=.026**		*Q=4.024 p=.900*	*Q=4.399 p=.001**	
	H	*Q=415.289 p=.001**	*Q=13.831 p=.001**	*Q=8.618 p=.001**	*Q=28.564 p=.001**	*Q=20.141 p=.082*	*Q=24.540 p=.001**
0.5	F	*Q=0.211 p=.900*			*Q=18.112 p=.001**		
	G	*Q=9.922 p=.001**	*Q=10.133 p=.001**		*Q=19.024 p=.001**	*Q=83.234 p=.001**	
	H	*Q=2.707 p=.295*	*Q=2.918 p=.243*	*Q=7.215 p=.004**	*Q=64.210 p=.001**	*Q=54.855 p=.001**	*Q=28.379 p=.001**
1	F	*Q=19.437 p=.001**			*Q=2.386 p=.390*		
	G	*Q=21.652 p=.001**	*Q=2.216 p=.448*		*Q=0.106 p=.900*	*Q=2.280 p=.425*	
	H	*Q=6.621 p=.007**	*Q=26.057 p=.001**	*Q=28.273 p=.001**	*Q=1.819 p=.600*	*Q=4.205 p=.070*	*Q=1.925 p=.552*

** Denotes statistical signifnicance (p<.05)*

C5.3. T-tests conducted on participant 3 assessing differences in friction between the thin and thick gloves chlorinated to the same concentration.

	Load	Dynamic	
		Dry	Wet
A-E	Low	*t(2)=-2.064 p=.175*	*t(2)=18.621 p=.003**
	Medium	*t(2)=10.433 p=.009**	*t(2)=-1.951 p=.191*
	High	*t(2)=-6.589 p=.022**	*t(2)=34.541 p=.001*
B-F	Low	*t(2)=23.696 p=.002**	*t(2)=2.774 p=.109*
	Medium	*t(2)=17.595 p=.003**	*t(2)=-71.294 p=<.001**
	High	*t(2)=-8.960 p=.012**	*t(2)=-12.179 p=.004**
C-G	Low	*t(2)=4.266 p=.051*	*t(2)=-37.379 p=.001**
	Medium	*t(2)=8.662 p=.013**	*t(2)=21.260 p=.002**
	High	*t(2)=0.532 p=.648*	*t(2)=0.826 p=<.001**
D-H	Low	*t(2)=124.862 p=<.001**	*t(2)=-19.007 p=.003**
	Medium	*t(2)=-16.654 p=.001**	*t(2)=10.435 p=.005**
	High	*t(2)=8.542 p=.013**	*t(2)=-9.725 p=.010**

** Denotes statistical signifnicance (p<.05)*

C5.4. T-tests conducted on participant 3 assessing differences in friction between the dry and wet conditions.

	Dynamic		
Glove Sample	Low Load	Mid Load	High Load
A	*t(2)=-0.890 p=.468*	*t(2)=85.889 p=<.001**	*t(2)=40.748 p=.001**
B	*t(2)=42.782 p=.001**	*t(2)=110.648 p=<.001**	*t(2)=-12.226 p=.007**
C	*t(2)=19.715 p=.003**	*t(2)=32.034 p=.001**	*t(2)=10.561 p=.009**
D	*t(2)=13.439 p=.005**	*t(2)=-3.203 p=.085*	*t(2)=4.387 p=.048**
E	*t(2)=33.119 p=<.001**	*t(2)=-1.107 p=.384*	*t(2)=8.174 p=.015**
F	*t(2)=-6.799 p=.021**	*t(2)=10.540 p=.013**	*t(2)=113.914 p=<.001**
G	*t(2)=2.176 p=.161*	*t(2)=61.761 p=<.001*	*t(2)=11.348 p=.008**
H	*t(2)=0.356 p=.756*	*t(2)=47.580 p=<.001**	*t(2)=3.683 p=.066*

** Denotes statistical signifnicance (p<.05)*

Appendix D – Supplementary data for Chapter Seven

D1. Friction coefficients of NBR gloves in each condition, with the different tools at each load.

	Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6		Tool 7	
	Load	CoF	Load	CoF	Load	CoF	Load	CoF	Load	CoF	Load	CoF	Load	CoF
	1.05 (±0.05)	0.26 (±0.01)	1.11 (±0.09)	0.51 (±0.05)	1.02 (±0.04)	0.57 (±0.01)	0.97 (±0.07)	0.47 (±0.01)	0.80 (±0.16)	0.74 (±0.11)	1.01 (±0.03)	0.36 (±0.06)	1.22 (±0.11)	1.05 (±0.09)
	2.18 (±0.01)	0.25 (±0.01)	2.08 (±0.03)	0.50 (±0.02)	2.05 (±0.11)	0.44 (±0.04)	2.09 (±0.11)	0.36 (±0.04)	2.00 (±0.01)	0.67 (±0.01)	1.95 (±0.08)	0.35 (±0.15)	2.03 (±0.02)	1.01 (±0.02)
Dry	3.01 (±0.04)	0.25 (±0.01)	3.03 (±0.09)	0.48 (±0.04)	3.02 (±0.07)	0.43 (±0.03)	3.05 (±0.02)	0.38 (±0.01)	3.03 (±0.06)	0.66 (±0.04)	2.90 (±0.06)	0.35 (±0.08)	2.98 (±0.19)	1.02 (±0.21)
	4.02 (±0.07)	0.26 (±0.02)	3.92 (±0.13)	0.45 (±0.05)	4.05 (±0.02)	0.44 (±0.01)	4.09 (±0.11)	0.43 (±0.07)	4.04 (±0.01)	0.66 (±0.01)	4.01 (±0.06)	0.26 (±0.07)	4.36 (±0.14)	1.06 (±0.17)
	4.97 (±0.15)	0.26 (±0.04)	5.02 (±0.11)	0.43 (±0.04)	5.16 (±0.17)	0.46 (±0.10)	4.98 (±0.01)	0.48 (±0.01)	5.03 (±0.04)	0.66 (±0.02)	4.95 (±0.04)	0.30 (±0.05)	5.36 (±0.25)	1.10 (±0.32)
	1.01 (±0.01)	0.24 (±0.01)	0.94 (±0.03)	0.55 (±0.02)	1.01 (±0.02)	0.59 (±0.01)	1.00 (±0.05)	0.39 (±0.01)	0.94 (±0.04)	0.32 (±0.01)	0.99 (±0.02)	0.52 (±0.01)	1.16 (±0.05)	0.36 (±0.09)
	2.10 (±0.07)	0.26 (±0.02)	2.03 (±0.06)	0.55 (±0.03)	2.02 (±0.12)	0.49 (±0.04)	2.00 (±0.07)	0.33 (±0.02)	2.00 (±0.01)	0.24 (±0.01)	2.08 (±0.02)	0.24 (±0.01)	1.98 (±0.03)	0.38 (±0.02)
Alcohol	2.97 (±0.05)	0.27 (±0.02)	3.11 (±0.02)	0.55 (±0.01)	3.01 (±0.07)	0.45 (±0.03)	2.95 (±0.04)	0.35 (±0.02)	2.96 (±0.08)	0.25 (±0.02)	3.04 (±0.08)	0.25 (±0.02)	3.01 (±0.07)	0.39 (±0.21)
	4.05 (±0.12)	0.28 (±0.04)	4.07 (±0.04)	0.56 (±0.02)	3.99 (±0.05)	0.43 (±0.02)	4.02 (±0.09)	0.39 (±0.05)	4.06 (±0.12)	0.25 (±0.03)	4.10 (±0.15)	0.26 (±0.04)	4.13 (±0.04)	0.41 (±0.17)
	4.95 (±0.29)	0.28 (±0.09)	4.93 (±0.10)	0.56 (±0.06)	5.18 (±0.10)	0.41 (±0.03)	5.07 (±0.03)	0.43 (±0.02)	4.93 (±0.10)	0.43 (±0.02)	5.12 (±0.04)	0.52 (±0.01)	5.23 (±0.12)	0.42 (±0.32)
	1.06 (±0.10)	0.31 (±0.01)	1.00 (±0.05)	0.46 (±0.02)	1.03 (±0.01)	0.42 (±0.01)	1.09 (±0.06)	0.27 (±0.05)	0.97 (±0.15)	0.21 (±0.04)	1.02 (±0.02)	0.37 (±0.02)	1.06 (±0.05)	0.53 (±0.05)
Mix	2.02 (±0.09)	0.26 (±0.02)	1.96 (±0.05)	0.47 (±0.02)	2.03 (±0.03)	0.44 (±0.01)	1.99 (±0.11)	0.35 (±0.05)	1.90 (±0.09)	0.25 (±0.01)	2.03 (±0.11)	0.24 (±0.05)	1.95 (±0.10)	0.33 (±0.09)
	3.01 (±0.07)	0.26 (±0.02)	3.05 (±0.05)	0.49 (±0.03)	2.93 (±0.05)	0.42 (±0.02)	3.03 (±0.07)	0.35 (±0.02)	3.06 (±0.01)	0.20 (±0.01)	3.06 (±0.03)	0.20 (±0.01)	3.04 (±0.05)	0.28 (±0.04)

	4.00 (±0.06)	0.28 (±0.02)	4.00 (±0.15)	0.50 (±0.08)	3.99 (±0.03)	0.40 (±0.01)	4.01 (±0.03)	0.33 (±0.01)	3.94 (±0.04)	0.17 (±0.01)	4.08 (±0.05)	0.16 (±0.01)	4.02 (±0.08)	0.28 (±0.06)
	4.93 (±0.04)	0.35 (±0.02)	5.00 (±0.06)	0.51 (±0.03)	4.96 (±0.05)	0.38 (±0.01)	4.97 (±0.06)	0.34 (±0.01)	4.99 (±0.05)	0.22 (±0.01)	4.80 (±0.07)	0.33 (±0.01)	4.89 (±0.06)	0.30 (±0.04)
Muci-n	1.02 (±0.03)	0.50 (±0.02)	0.96 (±0.04)	0.57 (±0.02)	1.03 (±0.05)	0.53 (±0.02)	0.92 (±0.04)	0.34 (±0.03)	1.07 (±0.03)	0.24 (±0.02)	1.09 (±0.02)	0.30 (±0.02)	0.97 (±0.05)	0.72 (±0.05)
	2.07 (±0.07)	0.52 (±0.04)	1.97 (±0.08)	0.51 (±0.04)	2.07 (±0.05)	0.49 (±0.02)	2.00 (±0.02)	0.38 (±0.01)	2.05 (±0.04)	0.50 (±0.02)	2.07 (±0.5)	0.56 (±0.05)	1.90 (±0.10)	0.83 (±0.09)
	2.99 (±0.10)	0.52 (±0.05)	3.06 (±0.07)	0.47 (±0.03)	2.95 (±0.09)	0.48 (±0.04)	2.78 (±0.16)	0.36 (±0.04)	3.08 (±0.05)	0.49 (±0.01)	2.96 (±0.03)	0.50 (±0.01)	3.04 (±0.05)	0.82 (±0.04)
	4.12 (±0.10)	0.53 (±0.05)	3.92 (±0.07)	0.46 (±0.02)	4.08 (±0.08)	0.48 (±0.04)	4.01 (±0.10)	0.32 (±0.02)	4.00 (±0.06)	0.44 (±0.01)	3.99 (±0.05)	0.44 (±0.01)	4.05 (±0.08)	0.80 (±0.06)
	5.12 (±0.06)	0.53 (±0.03)	4.99 (±0.09)	0.43 (±0.03)	5.09 (±0.08)	0.48 (±0.04)	5.17 (±0.01)	0.28 (±0.01)	4.98 (±0.06)	0.40 (±0.01)	5.04 (±0.07)	0.39 (±0.01)	5.03 (±0.06)	0.79 (±0.04)
Oil	1.03 (±0.05)	0.33 (±0.03)	0.99 (±0.07)	0.58 (±0.03)	0.96 (±0.02)	0.42 (±0.01)	1.07 (±0.03)	0.42 (±0.08)	1.00 (±0.01)	0.34 (±0.01)	1.08 (±0.03)	0.46 (±0.01)	1.04 (±0.07)	0.25 (±0.03)
	1.97 (±0.10)	0.40 (±0.04)	1.97 (±0.13)	0.55 (±0.07)	1.93 (±0.07)	0.36 (±0.02)	1.97 (±0.08)	0.39 (±0.03)	1.90 (±0.03)	0.16 (±0.01)	2.04 (±0.05)	0.16 (±0.01)	2.02 (±0.08)	0.27 (±0.03)
	3.00 (±0.10)	0.39 (±0.03)	3.04 (±0.11)	0.55 (±0.06)	3.05 (±0.10)	0.30 (±0.02)	3.01 (±0.11)	0.40 (±0.10)	2.94 (±0.07)	0.16 (±0.02)	2.95 (±0.02)	0.16 (±0.01)	3.09 (±0.02)	0.27 (±0.01)
	4.12 (±0.20)	0.37 (±0.06)	4.08 (±0.08)	0.56 (±0.05)	3.95 (±0.11)	0.27 (±0.01)	4.12 (±0.10)	0.41 (±0.06)	3.95 (±0.06)	0.16 (±0.02)	3.94 (±0.02)	0.16 (±0.01)	4.25 (±0.09)	0.28 (±0.03)
	4.88 (±0.15)	0.36 (±0.04)	5.07 (±0.07)	0.57 (±0.04)	5.02 (±0.23)	0.25 (±0.02)	5.02 (±0.07)	0.43 (±0.02)	4.98 (±0.10)	0.31 (±0.03)	5.04 (±0.11)	0.53 (±0.03)	5.15 (±0.15)	0.28 (±0.05)
Pow-der	0.96 (±0.06)	0.37 (±0.02)	0.96 (±0.05)	0.45 (±0.03)	0.98 (±0.02)	0.38 (±0.05)	0.98 (±0.05)	0.28 (±0.05)	0.96 (±0.05)	0.35 (±0.05)	0.96 (±0.05)	0.16 (±0.01)	0.96 (±0.03)	0.32 (±0.02)
	1.99 (±0.04)	00.31 (±0.01)	1.98 (±0.09)	0.51 (±0.05)	2.07 (±0.08)	0.33 (±0.03)	1.95 (±0.01)	0.34 (±0.02)	1.98 (±0.05)	0.31 (±0.02)	1.97 (±0.07)	0.31 (±0.02)	1.95 (±0.05)	0.33 (±0.03)
	2.99 (±0.09)	0.29 (±0.02)	2.85 (±0.14)	0.55 (±0.09)	2.97 (±0.03)	0.28 (±0.05)	3.04 (±0.01)	0.35 (±0.03)	2.99 (±0.04)	0.29 (±0.07)	2.95 (±0.06)	0.29 (±0.01)	3.01 (±0.21)	0.33 (±0.01)
	3.98 (±0.16)	0.28 (±0.04)	4.01 (±0.06)	0.57 (±0.05)	3.97 (±0.18)	0.24 (±0.05)	3.93 (±0.03)	0.35 (±0.05)	3.97 (±0.06)	0.29 (±0.03)	3.99 (±0.02)	0.29 (±0.12)	3.97 (±0.06)	0.33 (±0.03)

	5.05 (±0.07)	0.27 (±0.02)	5.14 (±0.05)	0.58 (±0.06)	5.07 (±0.11)	0.22 (±0.01)	5.04 (±0.03)	0.35 (±0.01)	4.94 (±0.09)	0.26 (±0.03)	5.08 (±0.10)	0.21 (±0.01)	4.90 (±0.08)	0.33 (±0.02)
	1.05 (±0.09)	0.22 (±0.02)	1.01 (±0.10)	0.7 (±0.04)	1.04 (±0.08)	0.37 (±0.09)	0.96 (±0.04)	0.28 (±0.02)	1.05 (±0.08)	0.23 (±0.10)	1.02 (±0.02)	0.34 (±0.02)	1.02 (±0.03)	0.42 (±0.01)
	2.11 (±0.01)	0.23 (±0.01)	2.00 (±0.07)	0.39 (±0.03)	2.08 (±0.03)	0.32 (±0.05)	1.94 (±0.15)	0.27 (±0.02)	1.96 (±0.025)	0.75 (±0.10)	2.03 (±0.02)	0.75 (±0.01)	1.96 (±0.04)	0.43 (±0.02)
Wat -er	3.08 (±0.05)	0.23 (±0.01)	3.08 (±0.09)	0.40 (±0.04)	3.08 (±0.08)	0.28 (±0.04)	3.03 (±0.01)	0.29 (±0.01)	2.98 (±0.08)	0.69 (±0.04)	3.07 (±0.04)	0.69 (±0.03)	2.94 (±0.04)	0.46 (±0.02)
	4.03 (±0.06)	0.22 (±0.01)	3.98 (±0.05)	0.40 (±0.02)	4.16 (±0.07)	0.24 (±0.17)	4.14 (±0.01)	0.30 (±0.06)	3.97 (±0.06)	0.63 (±0.02)	4.07 (±0.02)	0.62 (±0.13)	4.00 (±0.04)	0.49 (±0.03)
	5.05 (±0.04)	0.21 (±0.01)	5.04 (±0.07)	0.40 (±0.03)	5.09 (±0.15)	0.23 (±0.13)	5.03 (±0.01)	0.33 (±0.05)	5.07 (±0.09)	0.19 (±0.03)	5.07 (±0.03)	0.35 (±0.02)	4.94 (±0.02)	0.52 (±0.01)

D2. Friction coefficients of NRL gloves in each condition, with the different tools at each load.

	Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6		Tool 7	
	Load	CoF	Load	CoF	Load	CoF	Load	CoF	Load	CoF	Load	CoF	Load	CoF
Dry	1.04 (±0.04)	1.23 (±0.09)	1.19 (±0.07)	1.71 (±0.12)	1.09 (±0.02)	1.78 (±0.04)	1.10 (±0.08)	1.62 (±0.12)	0.93 (±0.03)	1.35 (±0.07)	0.97 (±0.01)	1.03 (±0.03)	1.18 (±0.04)	2.15 (±0.03)
	2.12 (±0.02)	1.60 (±0.03)	1.89 (±0.07)	1.86 (±0.08)	2.00 (±0.13)	1.43 (±0.23)	2.02 (±0.07)	1.49 (±0.07)	2.09 (±0.02)	1.25 (±0.04)	1.10 (±0.07)	1.18 (±0.12)	2.23 (±0.16)	2.22 (±0.07)
	2.95 (±0.06)	1.59 (±0.10)	3.03 (±0.08)	1.32 (±0.07)	3.12 (±0.05)	1.23 (±0.07)	3.11 (±0.08)	1.39 (±0.06)	3.02 (±0.02)	1.19 (±0.05)	3.01 (±0.06)	1.29 (±0.09)	3.02 (±0.06)	2.14 (±0.08)
	4.04 (±0.06)	1.53 (±0.07)	4.05 (±0.05)	1.46 (±0.04)	4.05 (±0.16)	1.58 (±0.20)	4.29 (±0.13)	1.23 (±0.08)	4.00 (±0.09)	1.14 (±0.12)	3.97 (±0.03)	1.14 (±0.03)	3.90 (±0.05)	1.84 (±0.08)
	5.08 (±0.12)	1.47 (±0.14)	5.02 (±0.03)	1.12 (±0.02)	5.18 (±0.26)	1.56 (±0.29)	5.26 (±0.12)	0.99 (±0.06)	5.02 (±0.08)	1.05 (±0.10)	4.98 (±0.08)	0.70 (±0.09)	5.35 (±0.32)	1.67 (±0.66)
Alcohol	1.08 (±0.04)	0.18 (±0.01)	0.97 (±0.04)	0.58 (±0.03)	1.03 (±0.02)	0.39 (±0.01)	0.24 (±0.10)	0.32 (±0.01)	1.02 (±0.01)	0.33 (±0.04)	1.12 (±0.03)	0.19 (±0.01)	1.04 (±0.02)	0.43 (±0.02)
	2.10 (±0.04)	0.24 (±0.01)	1.95 (±0.05)	0.66 (±0.03)	2.03 (±0.01)	0.28 (±0.01)	0.27 (±0.07)	0.35 (±0.01)	2.00 (±0.03)	0.24 (±0.11)	1.88 (±0.11)	0.24 (±0.03)	2.07 (±0.04)	0.46 (±0.02)
	3.03 (±0.09)	0.25 (±0.02)	2.98 (±0.17)	0.65 (±0.10)	3.10 (±0.12)	0.23 (±0.01)	0.24 (±0.06)	0.32 (±0.01)	2.99 (±0.05)	0.25 (±0.03)	2.95 (±0.01)	0.25 (±0.01)	3.07 (±0.04)	0.46 (±0.02)
	4.07 (±0.16)	0.25 (±0.04)	4.07 (±0.08)	0.62 (±0.04)	4.01 (±0.06)	0.20 (±0.01)	0.21 (±0.13)	0.28 (±0.06)	3.88 (±0.02)	0.26 (±0.15)	4.01 (±0.14)	0.25 (±0.04)	4.00 (±0.28)	0.45 (±0.12)
	4.97 (±0.05)	0.24 (±0.01)	5.05 (±0.12)	0.61 (±0.06)	5.14 (±0.02)	0.20 (±0.01)	0.19 (±0.06)	0.28 (±0.02)	3.88 (±0.02)	0.25 (±0.07)	4.81 (±0.07)	0.77 (±0.02)	5.15 (±0.05)	0.44 (±0.02)
Mix	1.05 (±0.05)	0.32 (±0.01)	0.97 (±0.03)	0.43 (±0.01)	0.94 (±0.01)	0.33 (±0.03)	0.98 (±0.01)	0.28 (±0.02)	1.02 (±0.01)	0.28 (±0.01)	0.99 (±0.05)	0.33 (±0.01)	1.02 (±0.03)	0.42 (±0.01)
	2.08 (±0.06)	0.24 (±0.01)	2.02 (±0.14)	0.38 (±0.06)	2.00 (±0.01)	0.33 (±0.02)	2.01 (±0.04)	0.27 (±0.07)	1.97 (±0.01)	0.25 (±0.04)	2.02 (±0.07)	0.25 (±0.01)	1.98 (±0.08)	0.31 (±0.01)
	3.01 (±0.11)	0.20 (±0.01)	2.93 (±0.01)	0.39 (±0.01)	2.93 (±0.01)	0.29 (±0.01)	2.98 (±0.01)	0.24 (±0.04)	3.06 (±0.01)	0.20 (±0.01)	3.02 (±0.02)	0.20 (±0.01)	3.03 (±0.11)	0.24 (±0.01)
	3.94 (±0.08)	0.17 (±0.01)	3.93 (±0.09)	0.41 (±0.04)	3.86 (±0.01)	0.26 (±0.01)	4.05 (±0.01)	0.21 (±0.01)	4.01 (±0.01)	0.17 (±0.01)	4.13 (±0.11)	0.16 (±0.01)	3.93 (±0.01)	0.20 (±0.01)

	5.02 (±0.08)	0.14 (±0.01)	5.11 (±0.11)	0.41 (±0.05)	4.99 (±0.01)	0.24 (±0.01)	4.95 (±0.01)	0.21 (±0.06)	5.02 (±0.01)	0.12 (±0.01)	4.92 (±0.10)	0.32 (±0.01)	4.91 (±0.10)	0.18 (±0.01)
Mucin	1.11 (±0.02)	0.56 (±0.02)	0.93 (±0.04)	0.78 (±0.04)	0.94 (±0.05)	0.44 (±0.03)	1.21 (±0.09)	0.43 (±0.04)	1.00 (±0.02)	0.47 (±0.02)	1.10 (±0.08)	1.10 (±0.06)	1.11 (±0.05)	0.97 (±0.06)
	2.03 (±0.09)	0.57 (±0.04)	1.99 (±0.04)	0.85 (±0.13)	2.08 (±0.06)	0.38 (±0.02)	1.98 (±0.05)	0.45 (±0.02)	1.94 (±0.03)	0.57 (±0.07)	1.95 (±0.05)	0.57 (±0.02)	1.97 (±0.10)	0.97 (±0.08)
	3.02 (±0.05)	0.50 (±0.01)	2.92 (±0.10)	0.83 (±0.08)	2.97 (±0.08)	0.34 (±0.02)	3.08 (±0.07)	0.46 (±0.07)	2.99 (±0.02)	0.50 (±0.05)	3.07 (±0.12)	0.49 (±0.03)	3.01 (±0.12)	0.85 (±0.06)
	4.00 (±0.10)	0.44 (±0.02)	4.01 (±0.06)	0.80 (±0.04)	4.04 (±0.04)	0.29 (±0.01)	3.98 (±0.02)	0.46 (±0.07)	3.98 (±0.01)	0.44 (±0.01)	4.21 (±0.09)	0.43 (±0.02)	4.05 (±0.12)	0.74 (±0.05)
	4.99 (±0.09)	0.39 (±0.02)	5.09 (±0.05)	0.77 (±0.03)	5.00 (±0.13)	0.34 (±0.01)	5.00 (±0.06)	0.46 (±0.11)	4.90 (±0.02)	0.54 (±0.01)	5.14 (±0.08)	1.03 (±0.01)	5.03 (±0.06)	0.67 (±0.02)
Oil	1.07 (±0.03)	0.22 (±0.01)	1.03 (±0.09)	0.29 (±0.05)	1.00 (±0.02)	0.22 (±0.01)	1.00 (±0.01)	0.22 (±0.01)	1.03 (±0.08)	0.22 (±0.01)	1.01 (±0.02)	0.68 (±0.01)	1.05 (±0.03)	0.09 (±0.01)
	2.13 (±0.15)	0.16 (±0.02)	1.98 (±0.12)	0.39 (±0.05)	1.98 (±0.04)	0.24 (±0.01)	1.88 (±0.07)	0.24 (±0.02)	2.00 (±0.03)	0.16 (±0.01)	2.26 (±0.66)	0.46 (±0.10)	2.13 (±0.06)	0.07 (±0.01)
	2.91 (±0.05)	0.17 (±0.01)	3.07 (±0.18)	0.39 (±0.07)	2.90 (±0.13)	0.23 (±0.02)	3.00 (±0.14)	0.23 (±0.02)	2.97 (±0.08)	0.17 (±0.01)	2.67 (±0.57)	0.36 (±0.09)	3.10 (±0.09)	0.07 (±0.01)
	4.00 (±0.08)	0.16 (±0.02)	4.03 (±0.08)	0.38 (±0.03)	3.89 (±0.15)	0.20 (±0.02)	4.15 (±0.07)	0.20 (±0.02)	4.00 (±0.23)	0.17 (±0.05)	4.11 (±0.13)	0.27 (±0.03)	4.06 (±0.08)	0.08 (±0.01)
	5.09 (±0.14)	0.18 (±0.04)	5.00 (±0.03)	0.37 (±0.01)	5.03 (±0.06)	0.22 (±0.01)	4.86 (±0.14)	0.21 (±0.01)	4.96 (±0.06)	0.18 (±0.01)	4.97 (±0.07)	0.29 (±0.02)	5.08 (±0.02)	0.09 (±0.01)
Powder	0.98 (±0.06)	0.39 (±0.01)	1.09 (±0.07)	0.51 (±0.06)	1.05 (±0.07)	0.29 (±0.03)	1.01 (±0.05)	0.39 (±0.02)	1.00 (±0.05)	0.39 (±0.01)	0.99 (±0.05)	0.36 (±0.01)	1.04 (±0.03)	0.29 (±0.01)
	1.87 (±0.06)	0.32 (±0.01)	1.93 (±0.04)	0.61 (±0.03)	1.93 (±0.04)	0.31 (±0.01)	1.94 (±0.07)	0.40 (±0.02)	2.06 (±0.03)	0.31 (±0.02)	1.92 (±0.04)	0.32 (±0.01)	2.03 (±0.10)	0.23 (±0.02)
	2.94 (±0.04)	0.29 (±0.01)	3.02 (±0.08)	0.62 (±0.05)	3.00 (±0.06)	0.27 (±0.01)	2.86 (±0.05)	0.38 (±0.02)	3.11 (±0.03)	0.29 (±0.02)	3.00 (±0.03)	0.29 (±0.01)	3.07 (±0.03)	0.21 (±0.01)
	4.00 (±0.02)	0.29 (±0.01)	3.95 (±0.11)	0.61 (±0.06)	3.92 (±0.15)	0.24 (±0.02)	3.99 (±0.04)	0.35 (±0.01)	3.93 (±0.07)	0.29 (±0.02)	3.95 (±0.08)	0.29 (±0.02)	3.97 (±0.09)	0.21 (±0.02)
	4.99 (±0.09)	0.29 (±0.03)	4.99 (±0.03)	0.59 (±0.01)	4.96 (±0.05)	0.24 (±0.01)	5.01 (±0.12)	0.34 (±0.03)	5.01 (±0.04)	0.32 (±0.01)	4.80 (±0.04)	0.32 (±0.01)	5.08 (±0.20)	0.21 (±0.04)

Water	1.03 (±0.03)	0.61 (±0.03)	0.94 (±0.02)	0.71 (±0.01)	1.08 (±0.01)	0.45 (±0.01)	1.03 (±0.04)	0.39 (±0.01)	0.99 (±0.03)	0.45 (±0.03)	0.98 (±0.05)	0.97 (±0.06)	1.01 (±0.02)	1.28 (±0.05)
	2.09 (±0.08)	0.75 (±0.05)	1.98 (±0.09)	0.67 (±0.06)	2.06 (±0.03)	0.39 (±0.01)	2.00 (±0.07)	0.34 (±0.02)	1.99 (±0.07)	0.75 (±0.05)	1.99 (±0.07)	0.75 (±0.04)	1.97 (±0.05)	1.55 (±0.08)
	3.04 (±0.13)	0.69 (±0.06)	3.00 (±0.07)	0.63 (±0.04)	2.95 (±0.03)	0.33 (±0.01)	3.01 (±0.14)	0.35 (±0.06)	2.97 (±0.02)	0.69 (±0.01)	2.96 (±0.08)	0.69 (±0.04)	3.16 (±0.13)	1.46 (±0.15)
	4.00 (±0.09)	0.63 (±0.04)	4.08 (±0.06)	0.61 (±0.03)	4.11 (±0.07)	0.28 (±0.01)	3.97 (±0.07)	0.37 (±0.03)	3.82 (±0.12)	0.64 (±0.05)	3.99 (±0.03)	0.63 (±0.01)	4.20 (±0.10)	1.37 (±0.11)
	4.95 (±0.13)	0.57 (±0.04)	4.89 (±0.09)	0.58 (±0.05)	5.11 (±0.08)	0.26 (±0.01)	5.04 (±0.01)	0.40 (±0.01)	5.12 (±0.09)	0.35 (±0.03)	4.97 (±0.11)	0.99 (±0.04)	5.00 (±0.09)	1.31 (±0.08)