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Performance of medical gloves

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Submitted for the degree
of
Doctor of Philosophy

November 2012

Abstract

A need for a more scientific approach to medical glove design, which incorporated performance requirements such as dexterity and tactility, was identified from discussions with manufacturers and a review of relevant literature. Based on the results of a review of existing test methods and interviews with a wide range of practitioners, a number of existing tests were identified for development and a number of new tests were proposed.

The test apparatus and methods were designed, refined and validated with small groups of participants, allowing recommendations to be made for a battery of realistic, repeatable tests by which medical glove performance can be comprehensively characterised.

The recommended tests covered three main areas of performance: manual dexterity, tactility, and grip and friction. As well as existing tests, including the Purdue Pegboard Test, the Crawford Small-Parts Dexterity Test and the Semmes-Weinstein Monofilaments, new tests were developed that better simulated the tasks carried out by practitioners, including a suturing test, the Simulated Medical Examination Tactility Test, the Pulse Location Test and the Roughness Perception Test.

Apparatus was also designed to measure the effect of gloves on grasping forces and to compare static frictional properties of gloves. Grasp force and friction measurements were taken for examination gloves using human subjects and with a specially-designed anthropomorphic device. The results were compared with those obtained using a number of other friction measurement methods. There was little consistency between the test results, and none gave a definitive answer as to which glove produced the highest friction in any given situation. Further development of the apparatus and validation of the method was recommended, as well as a more comprehensive study of glove friction and the effects of lubrication.

As part of the validation of the selected methods, analysis was carried out into the effect of glove material, thickness and fit on performance and the relationship between perceived and measured performance. Initial results suggested that glove fit had a greater effect on dexterity than tactility, with looser gloves reducing dexterity and tighter gloves reducing tactility. Glove thickness was found to be a significant factor in tactility, and in manual dexterity, where tactile feedback is required; thicker gloves and ‘double-gloving’ produced a reduction in tactility compared to thinner, single-layered gloves, and hence affected the ability to manipulate objects.

Analysis of user perception of performance and of the effect of glove material properties did not produce clear trends. However, initial findings suggested that, contrary to user perception, natural rubber latex did not perform significantly better than alternatives such as nitrile and vinyl. A number of possible explanations for the discrepancy were proposed, and recommendations were made for future work with a larger sample size, including analysis of stress and fatigue levels and performing tests in lubricated conditions.

Keywords: examination surgical glove, friction, tactility, dexterity, latex, nitrile

Acknowledgements

I would like to thank my supervisors, Dr Roger Lewis, Dr Matt Carré and Dr Nicolas Martin, for their support and for their valuable insights that helped shape the project. I would also like to thank BM Polyco Ltd. for supporting the project and providing copious amounts of medical gloves, as well as some test participants.

I would like to thank Sheffield Teaching Hospitals NHS Trust, and particularly Steve Brown, for allowing me to conduct interviews and testing with their staff and on their premises.

For assisting in designing, building and testing the rigs, I am indebted to a number of people, particularly Chris Grigson, Jamie Booth, Luke Buckley-Johnstone, Diyana Tasron and Sami Ghebache. I would also like to thank all the PhD and undergraduate students who volunteered with the testing, and my colleagues who helped with invaluable advice throughout the project, particularly Dr James Clarke and Xiaoxiao Liu.

Finally, I would like to thank Keith Mylon for his tireless proof-reading of the thesis.

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Glossary

The following is a glossary of technical and medical terms used in the thesis. Where these terms appear in the text, they are italicised.

Accelerator	a chemical agent that increases the rate of vulcanisation
Contact angle	the angle at which a liquid/vapour interface (i.e. the outer surface of a droplet) meets a solid surface
Distal	Situated away from the centre of the body or point of attachment e.g. the distal phalanx is at the end of the finger
Cutaneous sensibility	the ability to sense external stimuli through the skin
Elastohydrodynamic	lubrication regime in which elastic deformation of contact surfaces and lubricant film resistance both contribute to supporting the load
Interphalangeal joint	Any of the joints between the bones of the fingers or toes
Laparoscopic surgery	Keyhole surgery in the abdomen or pelvis
Phalanx/phalanges	Any of the bones in the fingers or toes
Proximal	Situated near to the centre of the body or point of attachment
Tactile spatial acuity	the smallest distance apart at which two tactile stimuli can be distinguished from each other
Typodont	a model of the mouth with teeth, gums and palate – see Figure A 33

1. Introduction

This thesis describes a three-year study examining the effect of medical gloves on the performance of medical practitioners. The performance aspects covered included grip and friction, dexterity and tactility. The work included evaluation of existing test methods, design of new ones, and comparative testing of a number of medical gloves.

1.1. Importance of the study

There are two basic types of medical glove: examination gloves are ambidextrous, usually non-sterile and come in five sizes (extra-small to extra-large); surgical gloves are sterile, come individually packaged in handed pairs and are usually available in half-inch intervals of hand girth. The two gloves are generally used for different purposes, and differ hugely in cost. Surgical gloves are used in the operating theatre for a variety of dextrous tasks, ranging from microsurgery on the eye or ear to bone-setting or hip replacement. Examination gloves are used for non-sterile procedures such as performing external or internal examinations, taking blood, emergency medicine, and also for most dental work.

Because the majority of clinical work is not as dextrous as surgery, less emphasis is placed on the performance of examination gloves. Until recently, both examination and surgical gloves were generally made from natural rubber latex (NRL or “latex”), although alternatives were available for known cases of latex allergy. However, the lack of regulation of manufacturing processes in the early years of mass-production meant that gloves often contained a high level of allergenic proteins, which led to a steady increase in the number of cases of latex allergy reported [1]. Although current guidelines from the NHS and the Royal College of

Physicians [2] recommend only that non-powdered, low-protein latex gloves be used, most Trusts have replaced latex in non-surgical situations with less-flexible alternatives [3] such as nitrile in order to remove the risk of latex allergy in patients and practitioners. However, surgeons have generally resisted moves to replace surgical gloves in the same way, because of the perceived reduction in performance when using non-latex alternatives.

With respect to the glove design process, there is little or no evidence that gloves are evaluated in terms of their effects on users' manual performance. All the currently available standards focus on the barrier integrity of the gloves (e.g. [4, 5]) by defining tensile strength, freedom from holes and tear resistance. Clearly, since the primary role of the gloves is to prevent the spread of infection, it is important that the design brief includes such requirements, but these are not necessarily incompatible with achieving the best performance.

What is recognised by surgeons is that performance also has an effect on safety, particularly in a surgical environment. Surgeons using gloves with less-than-optimal frictional properties, for example, will be more likely to drop instruments, to slip when performing delicate procedures, or to increase their stress levels when attempting to compensate. Similarly, practitioners who cannot feel a pulse through gloves when taking blood will be more likely to remove the gloves and increase their risk of infection. There is also a subjective element to the performance which must be considered, in that practitioners' comfort and confidence in their gloves may affect their concentration levels and therefore their ability to perform surgery over extended periods of time.

What is needed, therefore, is a set of repeatable, quantifiable and realistic tests that fully define the effects of a given glove on performance in a representative range of medical tasks. It may not be that there is one glove that performs best in all situations, since the requirements of the spectrum of medical practitioners are many and varied. However, medical glove design, particularly in regard to performance, needs to move towards a more scientific process that will allow quicker and more efficient development of gloves that are optimised for their intended purpose.

1.2. Aims and objectives of the study

The primary aim of the study was to develop a suite of tests by which the performance of medical gloves could be measured, in order to improve the design process and enable production of medical gloves that allow practitioners to perform tasks as effectively as possible. A secondary aim was to gain some understanding of what factors contribute to glove performance.

The objectives of the study were to:

1. Identify currently available tests that are suitable for evaluating medical glove performance
2. Identify where new tests were needed; design, test and evaluate them
3. Determine the relationship between glove properties (material, thickness, fit) and performance
4. Determine the relationship between perceived and measured performance
5. Make recommendations about future glove design and evaluation

Future research can then focus on developing new or improved materials, textures, coatings and moulds that can be evaluated against existing designs using the recommended tests. The information gathered on the relative benefits of currently available gloves and configurations (such as “double gloving”) can also be used to inform the decisions of those responsible for procurement of gloves and for forming guidelines on their use.

1.3. Structure of the thesis

The thesis commences with two literature reviews: the first surveys glove research to date; the second focuses on test methods relevant to glove design. The following chapter details a set of interviews that were conducted with medical practitioners. The data gathered from the reviews and interviews is used to determine the direction of the remainder of the research. Three areas of performance were selected for further study, and the next three chapters detail the design, testing and evaluation of test apparatus and methods in each area. The remaining chapters are concerned with the effect of glove fit on performance, the relationship between perceived and measured performance and the physical testing of glove properties. The structure is as follows:

Chapter 2. Review of Glove Research – a review of previous studies relating to gloves, both medical and non-medical, with particular emphasis on glove performance.

Chapter 3. Review of Tests Relevant to Gloves – a review of test methods that may be useful in evaluating medical gloves. Some of these have already been used to evaluate gloves, while others have been used for other purposes such as the evaluation of nerve or brain injuries.

Chapter 4. Interviews – a description of structured interviews with medical practitioners about glove use and medical tasks, including study design, ethical review, interview procedure and results.

Chapter 5. Direction of the Research – definition of the scope of the study, including a flow chart of the various components; selection of existing tests to include in the study, based on the outcomes of the reviews and interviews, including selection methodology and scoring charts; a brief for the design of new tests.

Chapter 6. Dexterity – a description of the experiments carried out to evaluate the usefulness of three existing dexterity tests in measuring medical glove performance, and the design and evaluation of a new suturing simulation test.

Chapter 7. Tactility – a description of: the evaluation of the Semmes-Weinstein Monofilaments for medical glove tactility testing; the development and testing of five new methods for evaluating and comparing the effects of medical gloves on tactile sensibility.

Chapter 8. Grip and Friction – a description of: the evaluation of existing friction and grip tests; the design and testing of a device to measure forces in grasping; and the design and validation of an anthropomorphic hand to simulate hand-object interactions during grasping.

Chapter 9. Glove Fit Evaluation – an analysis of data gathered in the testing to determine the effect of glove fit in various dimensions on the different performance aspects.

Chapter 10. Perceived vs. Measured Performance – a description of the method of evaluating perceived performance and an analysis of data gathered in the testing to determine how perceived performance in the tests relates to measured performance scores.

Chapter 11. Physical Properties – a description of the measurement of the properties of various medical gloves, including thickness, stress-strain characteristics and tear strength.

Chapter 12. Analysis and Discussion – analysis of all the data gathered in the study to determine what relationships exist between glove properties and performance, and what tests are necessary to fully define glove performance.

Chapter 13. Conclusions – the importance of the results for glove design, the relevance to glove selection for specific roles or tasks, and recommendations for further work.

2. Review of Glove Research

2.1. Introduction

Attempts to quantify the effects of gloves on manual performance have been going on since the Second World War, when the US Armed Forced commissioned Harvard University to look at the effects of handwear on manual dexterity [6]. Since then, the work has spread and now encompasses a wide variety of handwear and considers many different aspects of manual performance, including tactility, grip strength and friction. As early as 1988, a review [7] of the research on industrial gloves covered hand performance requirements, evaluation, selection, sizing, grasp force and dexterity testing.

In the 1980's, the Centers for Disease Control (CDC), an American organisation that promotes prevention and control of disease, published guidelines for health practitioners that recommended the use of "blood and body fluid precautions" when a patient was "known or suspected to be infected with bloodborne pathogens" [8, 9]. This included, amongst other things, the use of gloves where contact with blood or bodily fluid is possible. The recommendations were eventually extended for use with all patients, regardless of infection status. These "Universal Precautions" were introduced to hospital practice across the US, the UK and other countries.

The gloves that were produced as a response to this were almost exclusively made from natural rubber latex (herein referred to as "latex"), and were not always of the highest quality. It was not until later that issues regarding latex allergy emerged (e.g. [10]), leading to changes in design and material selection. These new synthetic materials, such as polyvinyl chloride (“vinyl”) and acrylonitrile butadiene (“nitrile”) behave differently from latex in terms of their elasticity, frictional properties and tear resistance. Unsurprisingly, this has prompted research into how these materials compare and what is required of medical gloves. A 2006 review [11] of glove literature includes some of the work done on medical gloves, although it focuses on many of the same areas as Riley and Cochran [7] and does not cover much of the research using real and simulated medical procedures.

In this chapter, a review of glove research is presented, with the aim of determining the state of knowledge regarding glove performance, how much of it can be applied to medical gloves, and identifying what further work is required. The review also aims to be broad in scope, bringing together all relevant fields that have a bearing on medical glove design, including hand anatomy and the psychology of grasping, as well as both controlled laboratory testing and realistic, applied tests.

2.2. Hand function

The hand is a complex control system involving actuation and feedback. Jones and Lederman [12] link the two to describe hand function using a continuum. At one end is tactile sensing, the stimulation of a passive hand, which gives information such as surface texture and temperature; active haptic sensing “involves the use of sensory inputs provided by the stimulation of receptors embedded in skin, muscles, tendons and joints,” and the hand is always active; prehension (grasping) is primarily a motor function, but uses sensory feedback to precisely control movements and forces; non-prehensile skilled movements include gestures and non-grasping activities such as pressing keys. All of these functions are vital to medical practice, whether it be in examination, surgery or in performing other everyday tasks such as taking blood. It is therefore important that we consider the effect of medical gloves on each of these functions.

2.2.1. Neurophysiology of the hand

In order to gain a better understanding of how grasping works, as well as to understand the processes of tactile exploration and active haptic sensing, we must first understand the system of tactile feedback in the hand.

The skin, muscles and joints of the hand all contain sensory receptors that convert natural stimuli into electrical signals [13]. All skin is made up of either two or three layers, depending on the classification of the adipose tissue layer [12, 13]. The glabrous (non-hairy) skin of the hand contains various tactile units, consisting of afferent fibres and endings, that measure force (mechanoreceptors), temperature (thermoreceptors) and pain (nociceptors).

Johansson and Vallbo [14, 15] used microelectrodes to record impulses from single nerve fibres and thus obtain information about nerve function and location. They estimated that there are 17,000 mechanoreceptors in the glabrous skin of the hand. About half of these are fast adapting (FA), i.e. they respond with a burst of impulses only at the onset and removal of the stimulus. The other half are slow-adapting (SA) – they respond with a sustained discharge. These can be split into two further categories (I and II).

“Each type of afferent fibre [FA I, FA II, SA I and SA II] is (presumed to be) associated with a specific type of ending.” [12] These endings are found at different locations in the skin that link to their function (see Figure 1).

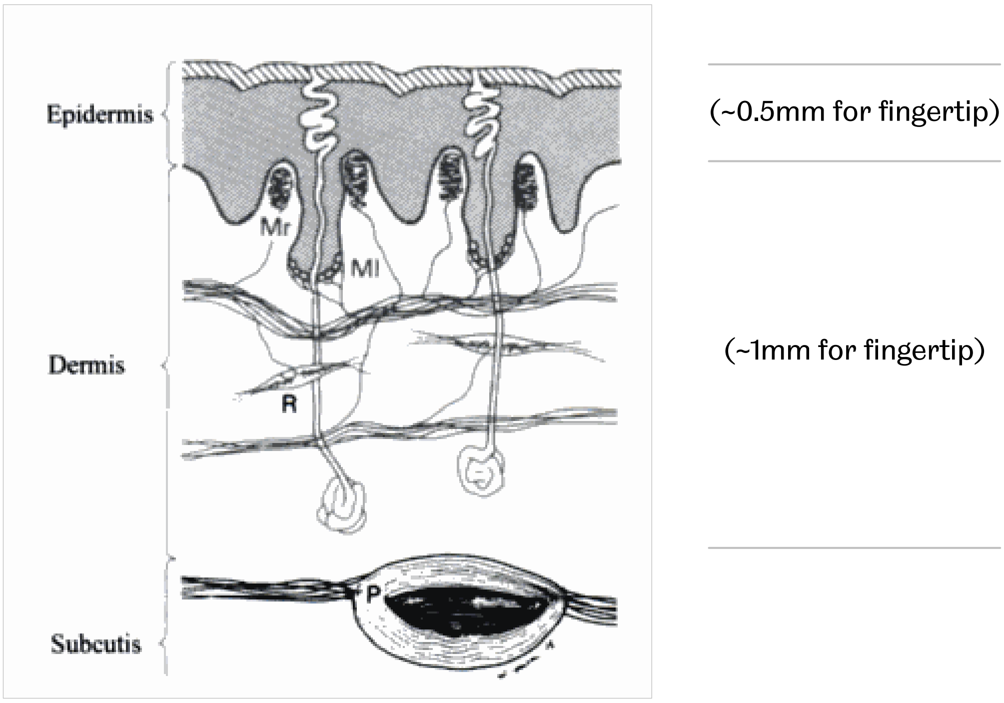

Figure 1. Vertical section through the glabrous skin of the human hand. Mr = Meissner corpuscle; Ml = Merkel cell neurite complex; R = Ruffini ending; P = Pacinian corpuscle (reproduced from [14], distances added).

FA I and SA I have small and well-defined receptive fields and are very sensitive to edge contours denting the skin, as opposed to the whole field being depressed, so are useful in spatial discrimination. These are associated with Meissner and Merkel endings respectively, which are near the surface of the skin. They are also concentrated in the fingertips, and there is “a striking decrease [in the density of these units] from the *distal* to the *proximal* half of the terminal *phalanx*,” [14] (see Figure 2) which is evident in a reduction in *tactile spatial acuity*.

FA II and SA II (30% of afferents in glabrous skin of hand) have a single zone of maximal sensitivity and wider surrounding area with gentle fall-off. They are associated with Pacinian corpuscles and Ruffini endings respectively, located deep in the dermis and subcutaneous tissues, and are sensitive to vibration and lateral skin stretch respectively.

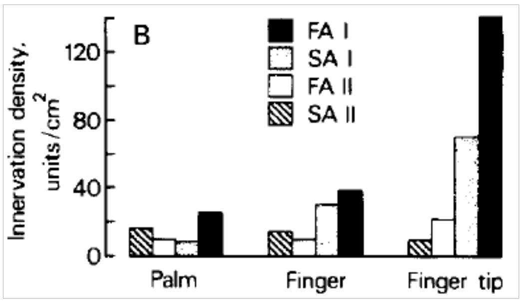

Figure 2. Histogram showing the density of innervation of the four types of mechanoreceptive units in different regions of the glabrous skin area of the human hand (reproduced from [14]).

These differences in function have been shown in practice by Phillips, Johansson, and Johnson [16], who mapped afferent responses when reading Braille. They found that FA I and SA I resolve the patterns well, but FA II and SA II do not.

Johansson and Vallbo went on to discuss the role of mechanoreceptors in motor control, and hypothesised that cutaneous sensors enable us to automatically balance grip forces. This is discussed further in the section on 'Grasping'.

2.3. Friction and lubrication

A key factor in hand function, in addition to neurophysiology, is contact friction. This affects both the ability to grasp and tactile perception. Much work (e.g. [17-21]) has been done to improve understanding of finger friction, which does not conform well to simple friction models. Cutkosky and Wright [22] came up with a number of models to describe friction in artificial fingertips for robotic hands, with different models being the most relevant depending on the contact area and fingertip radius relative to the object size.

Dinç, Ettles, Calabrese, & Scarton [23] measured finger friction on a simulated musical keyboard. They varied the humidity and surface roughness, compared the results with theoretical models, and concluded that tactile friction is primarily adhesive, but modified by liquid bridges. The same may well apply to glove polymers lubricated by bodily fluids.

A few studies have attempted to characterise medical glove friction. The key driver for this has been a desire to improve ease of donning for surgeons, particularly when hands are damp from ‘scrubbing up’. Roberts and Brackley [24] devised two experiments to measure glove friction on glass and fingertips. They found that increased hardness and roughness led to reduced dry friction, but that friction can increase in damp conditions. Anecdotal evidence suggests that nitrile is perceived to be more slippery than latex. However, Lewis et al. [25] found that dynamic, dry friction on steel was significantly higher for nitrile than for latex or bare hands. They found that in wet or oily conditions, all performed similarly. Laroche, Barr, Dong, & Rempel [26] actually found that wet static friction on a tool surface was higher for nitrile than latex.

The mechanisms and factors in both dry and lubricated friction of gloves are still not well understood, and further work is needed, both to identify the optimum value for a given task or role, and to relate the friction coefficient to intrinsic glove properties such as elasticity and hydrophilicity.

2.4. Grasping

In the interests of glove design, it is useful to classify grasps. Many attempts to have been made [13, 27] and one such example is shown in Figure 3 (this was intended to describe manufacturing grasps, but is useful as a general guide). The key distinction is between precision and power grip. In precision grips, the fingertips play a more important role in feedback and control, whereas in power grips, the emphasis is on stability, and the middle and *proximal phalanges* are in contact with the object. Both types are used extensively in medicine and dentistry.

2.4.1. Neurophysiology of grasping

Much of what we know about the role of tactile feedback in grasping comes from work done at the University of Umeå from the late 1970's onwards. Following on from Johansson and Vallbo's 1983 work on neurophysiology, Johansson and Westling [28] designed a grasping and lifting task using an instrumented rig to investigate the effect of cutaneous sensory cues on grasping forces.

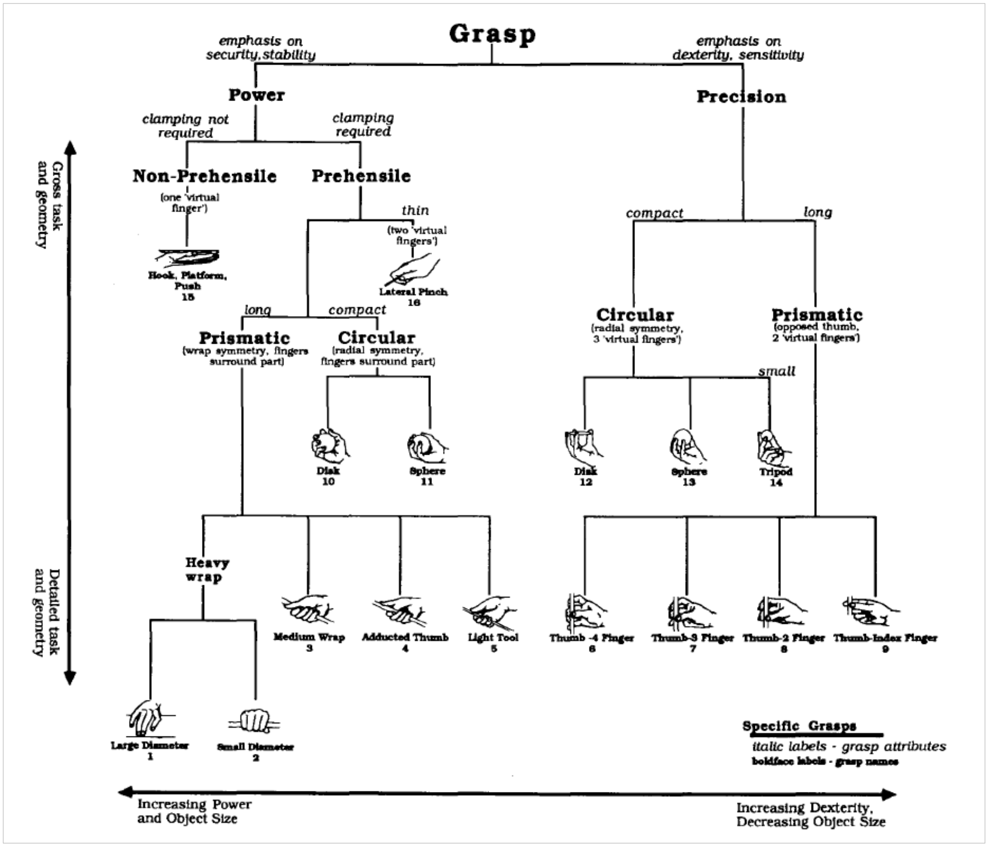

Figure 3. Taxonomy of grasps, modified from Cutkosky & Wright, 1986 (reproduced from [29]).

They found that the force balance at the fingertips was adjusted according to the friction at the contact surface to prevent slip whilst providing as small a safety margin (the ratio of actual grasp force to grasp force at the point of slipping) as possible to optimise comfort. By repeating the experiment with digital anaesthesia, they concluded that this control was based on cutaneous afferent cues – initial surface friction information and secondary adjustments in response to micro-slip, measured as vibration. They combined the two previous approaches in a further experiment [30], using microelectrodes to measure afferent responses during the grasp-and-lift task. They also extended the investigation to include stimulation of a passive finger with a force probe and electrical stimulation. They showed directly that tactile afferents are used in grip force adaptation, and that tactile stimulation by itself can trigger adjustment in forces, mostly in response to vibration cues, and to a lesser extent to localised frictional slips (see also [31-34]).

Further work at Umeå [35, 36] and elsewhere [37, 38] looked at multi-digit grasping and the co-ordination of fingertip forces, finding that each finger acts independently based on local frictional conditions. They also found that other forms of sensory input can be used to gain information if cutaneous senses are impaired [39].

Wheat, Salo, and Goodwin [40] applied normal and tangential forces to a static fingertip and determined the ability to perceive scale of increase, finding that cutaneous afferents give accurate information about both normal and tangential forces. Monzée, Lamarre, and Smith [41] carried out further experiments with digital anaesthesia in grasping and lifting, and found that loss of tactile sensation increases grip force and introduces torques from misalignment of fingers and imbalance in pressure between fingers, because the mechanoreceptors signal the source and direction of pressure applied to the skin, which is used to adjust and direct pinch forces. Cole [42] found a similar phenomenon when comparing grasp forces in older and younger people.

The relevance of these findings to understanding of the effects of gloves is evident, since the glove provides a barrier between the grasped object and the tactile units and hence will impair sensibility to a greater or lesser extent.

2.4.2. Effect of friction on grasp force

As well as looking at the way in which tactile information is translated to grasp force, we can also obtain information from grasp-and-lift experiments about the effects of varying frictional properties. Cadoret and Smith [43] used a linear motor to apply a constant normal force to the grasp apparatus (as opposed to a dead weight). They then varied the surface material, texture and lubricant. They found that friction is primary in determining holding and lifting forces and that they are not independently affected by texture or coating.

2.4.3. Glove testing

Early glove testing focused on gloves for military applications, such as flying and cold-weather gloves. Hertzberg [44] tested the effect of gloves on the grip strength of pilots using a hand dynamometer, and found a 20% decrease in strength.

Cochran, Albin, Bishu, and Riley [45] designed a new apparatus consisting of a handle wrapped in water-filled tubing which registers a change in pressure when grasped. They used it to rank various work gloves in terms of maximal exertion grasp degradation.

Further experiments were conducted with this apparatus and a dynamometer [46, 47] on a number of gloves for different applications. It was found that the tenacity (friction) and thickness had an effect on the maximal grasp force, but snugness of fit did not. Thickness was found to correlate well with reduction in strength compared to bare hands, with surgical gloves only causing a 4% reduction.

Other tests with EVA gloves used by astronauts (e.g. [48]) varied the level of exertion, and found that gloves had more effect on maximal than sub-maximal grasp force.

More information can be gained by using electromyography (EMG), in which electrical activity in muscles is measured. Sudhakar et al. [49] showed that while industrial gloves reduced grip strength, the level of exertion was the same as in the bare-handed condition, indicating that not all of the force is transferred to the object, some presumably being reacted by the stiffness of the glove. Mital, Kuo and Faard [50] measured torque when using screwdrivers and spanners, and found that gloves actually increased maximum torque, but that muscle exertion again remained the same. Conversely, Tsaousidis and Freivalds [51] found that there was no difference in maximum torque or pinch grip force with gloves, but did find a decrease in maximum grip force.

Willms, Wells, and Carnahan [52] carried out a combination of maximal and sub-maximal grasp tasks with different thickness rubber gloves and interdigital spacers using EMG. Their results agree with previous findings, that gloves reduce maximal grasp force, and also increase muscle activation required to apply a given force, suggesting that grasp efficiency is reduced by gloves. However, when Gnaneswaran, Mudhunuri, and Bishu [53] tested latex and vinyl examination gloves they found no significant effect on grip strength, since they provide little mechanical resistance.

While the mechanical effect of surgical gloves is fairly negligible, there is a neurological and psychological effect that becomes evident in sub-maximal grasp-and-manipulate tasks where precise force control is required. Lyman and Groth [54] assessed the effect of leather and surgical gloves on a grasping and manipulation task in which prehension force was measured. They found that wearing gloves increased prehension force, with the heavy leather gloves having the most effect, but noted:

> It is of interest [...] that even light surgeon's gloves appear to affect prehension force. This leads us to propose that the modus operandi for the effect of handcoverings on finger manipulation is to distort tactile cues. It may be speculated that this distortion takes the form of lowered tactile sensitivity and false cues from nonlinear transmission of information from the surface of the handcovering [... The] precise nature of the effect appears to depend on such properties as the friction and compressibility of the handcovering materials over the fingers.

Kinoshita [55] tested three thicknesses of surgical gloves in a pinch grip lifting task based on Johansson and Westling's apparatus [28]. He found that grip force, and therefore safety margin, increased with thickness, with bare hands having the smallest margin. This supports the theory that the gloves reduce or distort tactility, and the increased uncertainty leads to larger safety margins. R. H. Shih, Vasarhelyi, Dubrowski, & Carnahan [56] confirmed this by combining a similar experiment with sensory testing for multiple layers of latex gloves. They found that increasing the number of layers caused decreased sensitivity (increased pressure threshold) and an increase in peak grip force (and safety margin).

Since surgery can involve maintaining muscular exertion in grasping (such as retracting or manipulating tools) for extended periods of time whilst wearing gloves, an increase in grasp force will lead to greater hand fatigue. Thickness, material and other factors that affect tactile sensitivity must therefore be carefully considered in glove design.

Romano, Gray, Jacobs, & Kuchenbecker [57] attempted to remove the tactile barrier created by gloves using a tactile feedback system which produced vibrations in response to optical motion sensors. They found that the glove produced a dramatic improvement in response time to a slip when grasping an object. This may be a useful development, although it should be noted that the gloves used were much thicker than medical gloves and therefore caused a more substantial reduction in tactility.

2.5. Glove Effects on General Dexterity

The earliest attempts to identify glove effects on dexterity [6], used a cribbage board with cold-weather military gloves. The research focused on learning behaviour (the ability to overcome performance decrements by practice). Lyman [58] suggested that this learning is unique to the task, rather than to general glove performance. He also reported on research using a number of early dexterity tests with different hand conditions, including gloves, fingertip coverings and restraints, which showed that the major factor in performance decrement is concentrated at the fingertips, and that friction and stiffness have an effect. Bradley's [59] results agreed with this, and also found that snugness of fit correlated with dexterity.

Various studies have been done on chemical protective gloves [60-62] with a number of dexterity tests, which found differences in performance between gloves and an inverse relationship between thickness and performance.

It was not until the advent of “Universal Precautions” that research on medical glove dexterity started to appear. Brantley et al. [63] addressed worries that the widespread introduction of gloves would affect the development of psychomotor skills, concluding that it had no effect on trainee dentists.

Two studies investigated the effect of the thickness of latex gloves on dexterity. Nelson and Mital [64] found no difference in dexterity compared to bare hand in a paper cutting task, and Pourmoghani [65] found that there was only a difference in the fine dexterity tasks, in which he found thickness correlated with performance decrease.

Recent studies have focused on performance of latex-free examination gloves, with Berger et al. [66] finding a decrease in dexterity of about ten per cent with nitrile gloves compared to the bare hand condition, and Sawyer and Bennett [67] finding that fine finger dexterity was 8.6% higher with latex than nitrile examination gloves. Gnaneswaran et al. [53] found no significant differences in Purdue pegboard scores between latex and vinyl examination gloves.

2.6. Tactility and Active Haptic Sensing

2.6.1. Theory

Attempts have been made to describe how we use our fingers to explore our environment. Smith, Gosselin, and Houde [68] measured normal and tangential forces while exploring raised or recessed squares. They found that when they coated the fingertips with sucrose, the tangential force increased, but the normal force did not change. They concluded that shear forces in skin provide significant stimulus for mechanoreceptors during tactile exploration. Liu, Yue, Cai, Chetwynd, and Smith [69] looked at the correlation between actual and perceived values of friction, roughness and hardness. They concluded that the compliance of the fingertip could be a major factor in the way roughness is interpreted, and that it is very sensitive to contact pressure and sliding speed. According to Klatzky, Loomis, Lederman, Wake, and Fujita [70], material information gained from tactile sensors is not as important in tactile identification as the ability to explore geometry.

Wu [71] used optical coherence tomography (OCT) and ultrasound backscatter microscopy (UBM) to estimate the properties of fingertips (geometry, stiffness, deformation with various rigid indentors), and created an FE model which was used to predict stress and strain during tactile exploration.

2.6.2. Effect of gloves

As we have seen, the identification of shapes, textures and material properties is dependent on information from mechanoreceptors in the fingertips. The so-called ‘pressure threshold’ (the minimum applied *force* that elicits a response) is a good indicator of how well that information is transferred and has been used to measure the effect of barriers such as gloves.

Tiefenthaler, Gimpl, Wechselberger, and Benzer [72] tested latex examination and surgical gloves against the bare-handed condition using Semmes-Weinstein monofilaments (see Section 3.5) and found that the gloves significantly increased the pressure threshold, but found no significant difference between the gloves. No attempt was made to quantify the differences between the gloves, such as thickness or elasticity. Shih et al. [56] tested one, two and three layers of latex gloves and no gloves with monofilaments and found that pressure threshold increased with the number of layers, with two and three layers showing a significantly higher value than the bare-handed condition. They also found that reduced pressure threshold correlated well with an increase in dexterity. Kopka, Crawford, and Broome [73] tested three types of surgical gloves (neoprene, standard latex, and extra-thin latex) using modified von Frey hairs, and found that the threshold was significantly reduced for the thinner gloves, but latex and neoprene performed similarly. Strangely, although they were addressing the problem of loss of tactility due to gloves, they did not compare with the ungloved condition.

Neiburger [74] used a Correx dynamometer to measure the pressure threshold for dentists with and without latex gloves. A thirty-six per cent decrease in sensitivity was noted with the latex gloves.

Another commonly used test is two-point discrimination, which measures the smallest distance at which two points can be distinguished from each other (the *tactile spatial acuity*). Shih et al. [56] found some reduction with increased layers of latex gloves, but only on the thumb, and not on the index finger. This may be down to the localised fit, with loose material distorting or attenuating the tactile signals. Tiefenthaler et al. [72] found that gloves had no effect. These results are unsurprising given that *tactile spatial acuity* is largely dependent on the density of mechanoreceptors in the area of contact, rather than on the strength of the tactile signal.

Roughness discrimination may be a more realistic measure of tactile performance. Two studies [64, 75] compared the roughness discrimination of different gloves, and Wilson, Gound, Tishk, and Feil [76] compared gloved and ungloved performance with a dental explorer. None of them found significant differences, although two of them found a perceived difference in ability. Another roughness discrimination task [77] also found no reduction in tactility from gloves and no difference between gloves. The presence of perceived differences suggests that the either tests are not adequately assessing tactile ability or that gloves affect the confidence of the wearer but not their actual ability to discriminate.

Differences in tactile ability were, however, found in the study by Gnaneswaran et al. [53] using a newly designed tactility test in which participants identified lumps of glue on a sponge. They found that latex gloves performed significantly better than vinyl, despite the relative coarseness of the apparatus.

The effect of gloves on proprioception (the ability to perceive relative positions of body parts) was also tested by Desai and Konz [77] and Nelson and Mital [64] who measured the ability to identify pipe and hose diameters. Neither study found that gloves had an effect on proprioception. Shih and Wang [78] also found that gloves had no effect on the ability to discriminate weight.

Lederman and Klatzky [79] tested the effect of various manual constraints, including splints, rigid and compliant sheaths, probes and gloves, on the ability to identify common objects using haptic exploration. They found that gloves reduced the accuracy of identification by approximately two per cent.

What is clear from previous research is that gloves reduce or distort the transmission of tactile signals, and that thickness is a significant factor. What is unclear is the effect of fit, material and other properties on tactility, and how much the increase in pressure threshold affects haptic identification in real situations. Future testing needs to identify the cause of perceived differences between currently available medical gloves, and this will probably require improved resolution in test methods.

2.7. Effect of Gloves on Medical Tasks

In every day clinical and surgical practice, all of the aforementioned functions (grasping, dexterity, tactility and active haptic sensing) are combined in a range of simple and complex tasks, using a variety of tools or direct manual contact. The ultimate aim of the current study is to improve the performance of medical gloves in such tasks, and so it is useful to survey the work that has been done so far to analyse gloved performance in medical tasks.

Studies at the Ohio State University [80, 81] tested dental students in dental scaling tasks (one on real patients, one on *typodonts*). They found that wearing surgical gloves had no significant effect on scaling ability, completion time or tissue lacerations. Similarly, Hardison, Scarlett, Lyon, Cooper, and Mitchell [82] timed two dental tasks with and without gloves and found no difference in the time or quality of the work.

Neiburger [74] devised two dexterity tests based on dental tasks. Times for both tasks were slower with gloves on, but the test times were very short (between two and five seconds) and therefore errors in timing were likely to be significant (although no raw data is available and no statistical analysis was offered).

Some simpler nursing tasks were devised by Norton and Hignett [83] and tests were performed using various sterile latex and non-sterile latex, nitrile and vinyl gloves. They found that latex examination gloves performed better than nitrile, and both were better than vinyl. Participants also filled out a questionnaire about their perceived performance. In contrast to results in tactility tests described above, they found that subjective and objective results correlated well.

Gnaneswaran et al. [53] carried out some similar tasks with latex and vinyl examination gloves including: using a syringe, using scissors, and suturing. Results showed latex to be better than vinyl in some, worse in some, and in others it made no difference.

Investigations have been limited to selected areas i.e. dentistry and nursing, neither of which are considered to be the most critical for glove use (based on the fact that both usually wear examination rather than surgical gloves), and the results are somewhat inconclusive. There is therefore much more work needed to determine the effect of gloves on the range of medical tasks, so that appropriate gloves can be designed and selected for any given task.

Some recent studies [84, 85] have tried to identify the relative importance of dexterity in surgery, with both suggesting that it may not be the critical factor in many tasks. Development of more realistic test methods may help to provide further answers.

2.8. Durability and Puncture Resistance

Since the primary function of gloves is to prevent transmission of pathogens between the practitioners' hands and the patient, it is important that the integrity of this barrier is maintained. Practitioners are often working with sharp implements such as needles and scalpels, and may even be exposed to sharp tissue such as bone fragments which often tear the gloves. In particularly high risk situations, such as when the patient is known to have HIV, surgeons may wear a double layer of gloves, or even thick Kevlar® glove liners. Users must therefore choose between tear and puncture resistance on one hand and dexterity and tactility on the other, with the balance depending on the task to be performed and the risks involved.

The introduction of non-latex alternatives, particularly for examination gloves, has raised the question of whether they have comparable resistance properties. Various studies [86-91] found that failure rates were significantly higher in vinyl than latex.

Chua, Taylor, and Bagg [92] compared two latex examination gloves with a nitrile one, and found the failure rate to be significantly higher in the nitrile. However, the gloves were very different in thickness, and failure rate seems to correlate well with thickness, suggesting the material influence is less significant. Other studies [91, 93] found latex and nitrile to have comparable failure rates. Newsom, Smith, & Shaw [94] compared latex and neoprene surgical gloves and found the failure rates to be similar.

Other studies tested the effects of double-gloving and glove thickness on failure rates. Two of the studies [95, 96] concluded that double-gloving improves failure rates, but there are conflicting results on the effect of single-layer thickness. Nelson and Mital [64] produced gloves of different thicknesses in-house, which minimises other manufacturing variations, and they found a clear relationship between thickness and puncture resistance. Overall, this is probably the most widely covered area of glove performance. What are needed are clear relationships between intrinsic glove properties, puncture resistance, and usability (e.g. dexterity, tactility), so that gloves can be designed and selected appropriately.

2.9. Glove comfort and donning

As noted above, medical practitioners have previously identified difficulty with donning gloves, particularly when damp. A survey among dentists reported in Roberts and Brackley [97] showed that 76% of gloves were easy to don when dry, but only 39% when hands were slightly damp. They tested hydrogel-coated gloves against those normally worn and found a significant increase in reported ease of donning, as well as a reduction in both wet and dry friction, and a significant reduction in damp friction. Given the overwhelming uptake of hydrogel-coated surgical gloves, it is thought that more work in this area would not currently be profitable.

Dampness also causes discomfort. Powder has been used in the past to absorb moisture, but it is now not recommended or procured by the NHS due to its contribution to latex allergy [2]. Gnaneswaran et al. [53] compared latex and vinyl powdered and non-powdered gloves in terms of sweat generation. They found that, for non-powdered gloves, vinyl induced more sweating than latex, but the opposite was true when powdered. This would seem to recommend latex over vinyl for comfort. Further work on alternative low-cost moisture absorption technologies might be worthwhile.

2.10. Glove fit

Another common issue which has not yet been solved is poorly-fitting gloves and their effect on performance. It is thought that the snugness of fit is related to the elasticity of the material, which would explain the number of fit-related criticisms of nitrile examination gloves in hospitals that previously used the more elastic latex ones (see chapter 4). However, there are also a limited number of sizes, particularly in examination gloves, and in practice even less may be available at any one station, forcing practitioners to wear gloves that are either too restrictive or too baggy. What effect does this have on the practitioner's performance?

Robinette et al. [61] tested the effect on dexterity of various butyl chemical defence gloves. They found that there was a relationship between fit and dexterity. Smaller hands performed worse in the same sized gloves, despite performing similarly in the bare-handed condition. Tremblay-Lutter and Weihrer [98] extended the work, taking detailed hand measurements and identifying the optimum ease for best dexterity. They found that a negative ease (a tight fit) on the digit length and girth but a positive ease (a loose fit) on the palm girth was optimal. Kwon, Jung, You, and Kim [99] looked at relationships between hand dimensions to determine key dimensions for sizing, and suggested that hand length and circumference were the most representative. They also recommended different sizing systems for men and women.

Work on medical glove fit is very limited. Sawyer and Bennett [67] compared nitrile and latex gloves on dexterity tests and found that those with shorter fingers had reduced dexterity with nitrile gloves, but not with the latex, a result they put down to the reduced elasticity of nitrile compared to latex.

Further research needs to isolate fit from other factors and identify the dimensions that are key to performance. A study of the sensitivity of dexterity results to dimensional change could also yield useful information on the number of glove sizes needed.

2.11. Perception of performance

Chua et al. [92] conducted a study with orthodontists in which they were asked to use twenty pairs of three types of glove in normal practice and then complete a questionnaire. They found that thin latex gloves were preferred to standard latex or nitrile, although puncture resistance was worse. Comments suggested the preference was due to better tactility and more grip, and that they felt the thicker latex gloves significantly affected the speed of work. As has been stated already, there is a need for further study to link these results to quantifiable performance indicators in order to produce gloves that perform, and are perceived to perform, better.

2.12. Conclusions

Through more than sixty years of research, we have gained a reasonable understanding of the mechanisms by which gloves can impair performance – loss or distortion of tactile information, changes in frictional properties, restriction of movement, and so on. However, the application of these general principles to the specific area of medical gloves has not been thoroughly explored.

The minute dexterity of some of the tasks involved in medical practice requires much greater performance than, say, flying or even chemical handling. This is evident in the gloves that are used – medical gloves are much thinner and tighter-fitting than most types used in previous research. Small changes in properties such as thickness, fit and friction can have a large effect on performance, and assessing these effects is a difficult task.

While differences between bare hand and gloved performance are fairly apparent with current tests, the arguments over whether or not practitioners should wear gloves are long gone. The new battle is to find non-allergenic gloves that give the best possible performance for the given task or role. In order to optimise glove properties, test resolution must be fine enough to discriminate between broadly similar gloves.

Defining what factors contribute to medical performance is half the battle. Tasks can vary from grasping and using delicate instruments and power tools, to tactile exploration and examination, and will be different for each discipline. What work there has been in this area has focused on dexterity and used standardised tests designed for industrial selection. These tests, while a useful indicator of dexterity, do not necessarily simulate the skills required in medical practice.

There is therefore a need for tests that are repeatable, quantifiable and realistic. Once such a battery of tests has been developed, it is a simpler task to vary independently the properties of the gloves, such as thickness, grip pattern or material composition, and from the results to gain a more complete picture of how glove properties affect their performance. As new materials and manufacturing techniques are developed, glove designers and selectors will then have a tool kit through which they can provide medical practitioners with the best possible gloves for the task, enabling safer, more efficient medical practice.

3. Review of Tests Relevant to Gloves

Having determined a need for repeatable, quantifiable and realistic tests that can discriminate between medical gloves in terms of performance, an extensive review of literature concerning relevant tests was carried out. The aim of the review was to determine which tests showed most potential in terms of the repeatability, measurability, realism and, most importantly, the ability to discriminate between gloves. The findings were used to inform the selection of tests to be used or developed in this study, with the eventual aim of producing a battery of tests that could fully and accurately describe medical glove performance.

The review includes the limited literature on the effect of gloves on manual performance, but also covers the much wider areas of dexterity and tactility testing, finger friction and grip. A number of tests developed by others at BM Polyco Ltd and The University of Sheffield are also included. Those tests that are already designed to simulate medical tasks are treated separately, but may come under a number of the other categories.

3.1. Grasping

A basic requirement of all gloves is to grasp and manipulate objects. A number of tests that assess the effect of gloves on grasping are listed in Table 1, including both maximal and sub-maximal grasping.

Table 1. Grasping Tests

Test/Equipment	Primary Ref.	Other Refs.	Performance Tested	Apparatus
Variable hand dynamometer	[100]	[44, 46, 47, 49, 53, 101-107]	Maximum Applied Force	Figure A 1
Split cylinder	[107]	[108]	Grip force	Figure A 2
Cylinder/holed board	[58]	[54]	Applied prehension force over time	Figure A 3
Muscle force transducer	[58]		Muscular force	Figure A 4
Cylinder/light bank manipulation test	[109]		Grip force/safety factor (see also dexterity)	Figure A 5
W&J-type pinch grip force transducer	[32]	[28, 30, 33, 41, 43, 55, 56, 110, 111]	Grip force, safety factor	Figure 133
Handle pull/torque	[112]	[113]	Maximum friction force	Figure A 6
Tube squeeze	[45]	[46, 47, 51]	Maximum applied pressure	Figure A 7
Dynamometer w/EMG	[49]		Grip efficiency (grip strength/muscular exertion)	Figure A 8
B&L (or other) Pinch gauge	[102]	[51, 103, 105]	Maximum applied force	Figure A 9
Screwdriver and wrench torque with EMG	[50]		Applied force and muscular exertion	Figure A 10
Data Glove	[114]		Applied pressure pattern	
Tekscan pressure measurement	[115]	[107]	Applied pressure pattern	
Sollerman Hand Function Test[1]	[116]	[117]	Ability to perform task	Table A 1

Grip and pinch dynamometers were originally designed to measure hand strength in order to aid in the diagnosis or rehabilitation of patients with reduced neuromuscular function. The hand dynamometer has also been used to test the effect of gloves on grip strength in a range of applications. However, the majority of research (e.g. [44, 102]) has been conducted using thick gloves that may restrict hand movement. With medical gloves, the maximum applicable force is unlikely to be significantly affected. Hence, the dynamometer will not differentiate between bare hands and gloves, and certainly not between different types of medical gloves.

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[1] See also Section 3.3.

Previous work [47, 53, 101, 105] has confirmed this, finding no significant difference in grip strength between surgical gloves and bare hands.

A further problem is that applied force at maximum exertion also varies a great deal from test to test based upon the fatigue level of the participant, as well as other factors such as motivation and muscle condition. Furthermore, the dynamometer test encompasses a number of different characteristics of the glove and therefore is not very useful in determining the effect of individual characteristics on performance.

EMG (electromyogram) analysis has been used in conjunction with the hand dynamometer to show that loss of grip strength with gloves is due to a loss of force in the hand-glove interface rather than a reduction in the level of muscle exertion [49, 50].

Variations on the grip strength test include a split cylinder with a force gauge and a tubing-wrapped handle which measures pressure increase. The tubing-wrapped handle found even less force degradation for gloves than the dynamometer. To test precision grip strength as opposed to power grip, a pinch gauge, which works much the same as the dynamometer, can be used. This is probably more relevant to most surgical tasks, such as suturing and incision.

Tests such as Riley's hand pull [112], which measures the maximum horizontal force applied to a handle, combine the coefficient of friction and the maximum grasp force. While these tests are more dependent on glove properties than the hand dynamometer, they still depend on exertion levels. To apply a constant force while still simulating realistic conditions, artificial fingertips (e.g. [118]) could be attached to a force actuator.

A useful and realistic measure of the physiological effect of gloves on gripping is achieved in sub-maximal exertion tasks. Lyman and Groth [54, 58] designed a manipulation test using a split cylinder, in which the prehension force was measured while the cylinder was moved between multiple holes. They also produced a similar test [109] that introduced a light bank on which a timed sequence was indicated. This allows for speed and output rate to be measured. They found that prehension force increased as the coefficient of friction decreased, but that it was unaffected by any reduction in *cutaneous sensibility* due to the gloves, as were the speed and output rate. However, the authors admitted that, since the task did not require a high degree of manual dexterity, 'this may partly account for the failure to find consistent changes in performance speed as well as the lack of performance decrement attributable to distortions of sensory cues'. The experiment could possibly be improved by altering the shape of the instrument or modifying the task to increase the level of dexterity required.

Westling and Johansson's pinch grip rig [32] measures grip and load forces during lifting and holding of free weights. Kinoshita [55] used the rig to test a number of different glove conditions, including rubber surgical and chemical gloves. In contrast to Groth and Lyman's experiments [109], the coefficients of friction for these were not significantly different, so that the effect of glove thickness on grip force could be independently measured. It was found that the safety factor (the ratio of grip force to slip force) increased significantly, and almost linearly, with glove thickness. Time to apply the load was not significantly affected. This supports the theory that, while users can adjust to glove condition so that performance is not significantly affected, reduced tactile sensation when wearing thicker gloves will cause increased hand fatigue. However, when using similar apparatus, Shih et al. [56] did not find a significant relationship between grip force and thickness.

This apparatus seems to have the most potential for differentiating between medical gloves, and can be adapted in a number of ways. The parallel discs can be replaced with different materials and shapes and, as demonstrated by Johansson and Westling [30], transparent discs can be used to enable video monitoring of fingertip contact.

The "Data Glove" [114] consists of a baseball batting glove to which force-sensitive resistors are attached at the fingertips. The Tekscan® pressure measurement system consists of a thin film that can be wrapped around any surface and measures the pressure distribution. Both of these methods are much more flexible than instrumented pinch grip rigs, in that they can be used for almost any task, but are much more expensive and difficult to set up. They also have the disadvantage that they interfere with the results. The "Data Glove" cannot realistically be used with medical gloves as it will impede dexterity, and the Tekscan® film will alter the frictional properties of the surface.

The Sollerman hand function test [116] uses a number of basic tasks to measure hand function. The potential for use in discriminating between gloves is limited by the very coarse scoring system.

3.2. Pure Friction

In addition to tests that measure the overall effect of gloves on grasping, some isolate the frictional element, which has wider implications for glove use. While high friction is generally better when statically grasping instruments, it may be an impediment when manipulating medical devices and materials. The key tests for measuring glove friction are listed in Table 2.

Table 2. Pure Friction Tests

Test/Equipment	Primary Ref.	Other Refs.	Performance Tested	Apparatus
UoS finger friction rig	[25]		Static/dynamic friction	Figure 121
Polyco friction angle rig			Static friction	Figure 126
Force probe stimulation	[30]		Coefficient of Friction	Figure A 11
Keyboard transducer	[23]		Coefficient of friction	Figure A 12
Rubber hemisphere friction test	[119]		Coefficient of rubber/glass friction	Figure A 13
Balanced pivot finger friction test	[119]	[97]	Coefficient of rubber/finger friction	Figure A 14
Universal Micro-Tribometer (UMT)	[120]		Real-time friction	Figure A 15
Dental tool on force plate	[26]		Friction coefficient	Figure A 16
Linear translation stage	[121]		Friction coefficient	Figure A 17
Elastohydrodynamic tribometer	[122]		Elastomeric wet/dry friction behaviour	

In contrast to the grip and friction tests, which include the effect of the glove on the user, pure friction tests are a measure of the material properties and surface characteristics of the glove. However, in many of the tests, there is still too much reliance on human interaction. The University of Sheffield finger friction rig [25] calculates finger-surface sliding friction by measuring normal force and friction force at the contact. However, the friction coefficient may be influenced by both the sliding speed and the angle of attack, both of which depend on the user. Consistent static friction measurement with the rig is even more difficult.

Dinç et al. [23] designed a similar rig using a keyboard key and a piezo-electric force transducer to measure dynamic friction, and found that the coefficient of friction varied with sliding speed and normal load. The Universal Micro-Tribometer [120] achieves a similar result by applying a moving normal load and a constant. Results also showed a variation of friction coefficient with normal load.

In terms of static friction measurement, the Polyco friction angle rig (*Figure 126*), which measures the angle of an incline at which a mass slips, is promising. It mostly removes the element of human interaction in force application, but judgment is needed to detect when slip occurs. Depending on the lubrication regime, slippage can be gradual or very sudden. This could be improved by using an accelerometer or displacement sensor.

Roberts' glove and finger friction tests [97, 119], while aimed at investigating hand-glove friction, have some advantages. The rubber hemisphere (Figure A 13) simulates to some extent the compliance of a finger, so that the change in area of contact with load is taken into account. It also allows for a constant load to be accurately applied. If calibrated well, the balanced pivot finger friction test (Figure A 14) also allows a relatively constant force to be applied by the finger, using a mark to maintain the beam in a horizontal position.

The experiment by Laroche et al. [26] used a dental tool attached to a force plate. By applying a force on the thumb via a mass, rather than grasping the tool with thumb and fingers, the applied force is kept reasonably constant. The force plate also allows for accurate measurement of both normal and friction force in a similar way to the Sheffield finger friction rig, while allowing real tool surfaces to be tested. They found a difference in coefficient of static friction between wet nitrile and latex examination gloves on textured tool surfaces, but no difference on smooth surfaces.

André et al. [121] use similar equipment to Westling and Johansson [32], but apply a constant normal force and an increasing tangential force to measure coefficient of friction at slip. The apparatus is a little complex compared to other finger friction measurements, but the use of change in centre of pressure on the pads to detect slippage appears to be a much more accurate method than others used.

The force probe (see Figure A 11) also works in a similar way, except that the finger is passive. A normal force is applied to the fingertip and the tangential force increased until slip occurs. Tangential and normal force and acceleration are measured and the friction coefficient calculated. This minimises the effect of muscular force, and allows for a more consistent applied force. In Johansson and Westling's experiment [30], the probe is hand-held, but it is thought that it could be adapted to be applied mechanically.

An *elastohydrodynamic* (EHD) tribometer, which measures contact area and lubricant film thickness, was used by Deleau et al. [122] in a lubricated rubber-glass contact (a simulation of windscreen wiper operation). While this could provide some useful information on the differences in wet grip experienced with different gloves, it is thought to be a little costly for this study.

3.3. Dexterity (non-medical)

Many dexterity tests have been designed, mostly with the aim of assessing the motor skills and hand-eye co-ordination of potential employees or for aiding in the rehabilitation of patients with brain or motor injuries.

Some of these tests have already been used or adapted for measuring the effect on dexterity of wearing gloves, but it may be that others can be used to give better results. Table 3 shows the tests that are reviewed in this section. Some tests have also been designed that seek to simulate specific medical tasks or use medical instruments. While many of these tasks involve dexterity, they are considered separately in Section 3.6.

Table 3. Dexterity Tests

Test/Equipment	**Primary Ref.**	**Other Refs.**	**Apparatus**
Cribbage board	[6]		Figure A 18
Minnesota Rate of Manipulation Turning (MRMTT)	[123]	[58, 61, 62]	Figure A 19
Purdue Pegboard	[124]	[53, 66, 67, 123, 125]	Figure A 20
Grooved Pegboard	[65]		Figure A 21
O'Connor Finger Dexterity	[126]	[61, 62, 66, 123, 127]	Figure A 22
O'Connor Tweezer Dexterity	[105]		Figure A 22
Santa Ana Finger Dexterity	[123]		Figure A 23
Knob setting	[58]		
Craik Screw Test	[58]		
Plug Insertion Test	[58]		
Cylinder/light bank manipulation test	[109]		Figure A 24
Bennett Hand-Tool Dexterity Test	[128]	[60, 62]	Figure A 25
Pennsylvania Bi-Manual Worksample Assembly Test (PBWAT)	[129]	[61]	Figure A 26
Crawford Small Parts Dexterity Test	[130]	[61, 131]	Figure A 27
Electrical socket assembly	[113]		
Rifle disassembly/assembly	[62]		
Knot-tying test	[102]		
Nuts-and-bolts test	[102]		
Cutting out paper shapes	[64]	[53]	
Lining up taps	[83]		
Drawing pins and tweezers	[83]		
Sollerman Hand Function Test[2]	[116]	[117]	Table A 1
Coin Rotation Task (CRT)	[132]		

3.3.1. Pegboard-type finger dexterity tests

Griffin [6] used a cribbage board to study the effect of cold-weather military gloves on dexterity. The basic method involves moving pegs from one hole to another, with the total time taken to move a number of pegs being recorded. Following this, a number of variations on the theme were designed. In 1948, Tiffin designed the Purdue Pegboard Dexterity Test [124], which was used to differentiate between potential employees in industrial work. This expanded the test procedure to include an assembly task with washers and collars, increasing the amount of fine dexterity

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[2] See Section 3.1 for discussion.

required. The O'Connor Finger Dexterity Test [126] involves picking up multiple pins of a smaller diameter. This requires finer dexterity than the Purdue test.

Further variations on the pegboard finger dexterity test include the Santa Ana Finger Dexterity test (described in [123]), in which square pegs with circular tops are rotated 180° in their holes as rapidly as possible; the Grooved Pegboard Test (described in [65]), in which keyed pins are placed in holes which have randomly positioned slots; and the Minnesota Rate of Manipulation Test (described in [123]). This has two parts – Placing (putting pegs in holes) and Turning (removing them with one hand, turning them over with the other and replacing). It uses much larger pegs (37mm diameter).

Berger et al. [66] compared the Purdue and O'Connor pegboard tests for gloved and ungloved conditions and in wet and dry conditions, and found that, while both tests can discriminate between the gloved and ungloved conditions, only the O'Connor test produced different results for the wet and dry conditions. Sawyer and Bennett [67] found that the Purdue assembly task produced a statistically significant difference between nitrile and latex gloves, whereas the combination pegs-in-holes test showed no significant difference. Pourmoghani [65] found that there was a clear relationship between glove thickness and performance in all of the Purdue tests. He found the same for the Grooved Pegboard Test.

3.3.2. Hand-tool dexterity tests

The Crawford Small Parts Dexterity Test (CSPDT) [130] consists of two parts. In the 'Pins and Collars' part, tweezers are used to insert small pins into close-fitting holes in a plate and then place collars over them. The second part is the 'Screws' test, in which small screws are placed in holes in a plate and screwed down with a screwdriver. There is little data to confirm the reliability or validity of the test [133], and one study [134] has shown that changes in parts and tooling have invalidated the original test norms, particularly of the ‘Screws’ part. However, in some studies comparing dexterity tests, the CSPDT has shown promising discrimination between gloves (see Section 3.3.3).

Norton and Hignett [83] designed a test similar to the CSPDT ‘Pins and Collars’ that involved moving drawing pins from a pot with tweezers. They found that the test did not discriminate well between gloves.

In the Bennett Hand-Tool Dexterity Test [128], spanners and a screwdriver are used to loosen, relocate and tighten bolts, nuts and washers of various sizes. This uses a good mixture of manual and tool manipulation and grips of different sizes. The test is quite long, which could make it difficult to gather sufficient data. Bensel [62] reduced the test to two assemblies per size to reduce time. This was found to be equally effective. In terms of discrimination, Plummer et al. [60] found that the time taken to complete the test was significantly increased by double-gloving, but that the difference between three types of hazardous material handling gloves (when worn as a single layer) was not significant.

Bishu et al. [102] describe a very similar test to the Bennett test, where the nut and bolt are unscrewed without tools. They found a greater effect from gloves for smaller nuts and bolts. The Pennsylvania Bi-Manual Worksample Assembly Test (PBWAT) [129], also involves screwing nuts and bolts together manually. In the Craik

Screw Test (described in [58]), screws are unscrewed from holes and screwed into adjacent holes.

Other tests

Early tests, measuring the effect of gloves on the dexterity of pilots, were based around setting flight controls, such as the angular position of knobs (e.g. [58, 59]). Norton and Hignett [83] designed a similar test positioning taps. However, as Lyman [58] points out, 'because reaching and positioning movements depend more on information from the muscles and joints and on gross visual cues than on glove-object interactions, it may be expected that such movements will tend to be relatively unaffected by hand coverings' (p. 94). The same could be applied to the Plug Insertion Test [58].

Bishu et al. [102] designed a knot-tying test, with different sizes of rope. They found that gloved performance was much worse than bare-handed, but that there was no significant difference between gloves or between rope sizes. A similar test is used to train surgeons, where thread is tied in a reef knot with instruments.

The rifle disassembly/assembly task [62] can be discounted as it is really only possible in a military environment. There are many tests involving household objects and tasks. The Sollerman hand function test [116] involves a good range of tasks, but the dexterity required is generally very low, and the scoring is very coarse. Two studies tested the effect of gloves on subjects' ability to cut out shapes in paper, both quickly and accurately. Gnaneswaran et al. [53] found that the type of glove (latex or vinyl) had a significant effect on performance. Nelson and Mital [64] found that glove thickness had no significant effect on the task. The Coin Rotation Task [132] is a simple test which measures pure dexterity, and therefore is promising for glove testing. An electrical socket assembly task designed by Chen et al. [113] showed good discrimination between thicker gloves, although it replicates the screwdriver dexterity in more established tests like the CSPDT.

3.3.3. Comparison of tests

Gauvin et al. [135] evaluated a number of dexterity tests with respect to their ability to discriminate between different types of gloves. They found that the tests that worked best at the fine end of the dexterity scale were: Crawford Small Parts Dexterity Test – Screws and O'Connor Finger Dexterity Test.

Robinette and Armstrong [61] compared the O'Connor Finger Dexterity Test, the PBWAT, Crawford – Screws and MRMTT. They found that all tests showed significant differences between gloved and ungloved performance, and between the Nomex-over-butyl and the other gloves. However, the Crawford – Screws test could not discriminate between the three thinner gloves.

3.4. Active Haptic Sensing

Active haptic sensing is the process of manual exploration by which information about objects, such as size, shape, weight and texture is gained. It includes both tactile sensation and kinesthesia (the perception of body position and movement and muscular tensions). In this section, a number of haptic tests are reviewed. They are listed in Table 4.

Table 4. Active Haptic Sensing Tests

Test	Primary Ref.	Other Refs.
Knob identification	[58]	
Haptic Identification of Common Objects	[79]	
Pipe diameter identification	[64]	
Weight Discrimination	[78]	
Shape/Texture Identification (STI)	[127]	[117, 136]

Hunt and Craig (cited in [58]) studied the effect of light flying gloves on this ability by asking subjects to identify different knobs while blindfolded. They found that errors in identification increased by more than fifty per cent when wearing the gloves, compared to bare hands. The test could probably be adapted from flying controls to something more identifiable by the general public.

Lederman and Klatzky [70, 79] designed an experiment in which subjects were required to identify 38 common objects while constrained in various ways, such as a rigid finger sheath or splinting, or using only a rigid probe. With the sheathed finger and with the probes, the accuracy and response time were significantly worse than with a bare, unconstrained finger. Significantly for the study of medical gloves, the accuracy with a knitted glove was not significantly different from the bare hand, but the response time was significantly greater, suggesting that the lack of cutaneous cues impedes haptic identification. Whether the difference is significant with medical gloves is yet to be tested.

Nelson and Mital [64] studied the effect of the thickness of examination and surgical gloves on dexterity and tactility. One of the ‘tactility’ tests might better be described as a haptic identification task. Subjects were asked to select a pipe of given diameter from a choice of three. The time to complete the task was measured, with errors incurring a time penalty. However, they found no significant effect of glove thickness. There seemed to be a slight trend, which might be emphasised if the difficulty of the task was increased, for example, by adding more pipes, or by making the diameters more similar.

Shih and Wang [78] tested the effect of gloves on weight discrimination, and found no significant effect. It is not thought that this is worth pursuing with surgical gloves, as it is both irrelevant to medical application and unlikely to be significantly affected by the gloves.

Rosén and Lundborg [136] designed the Shape/Texture Identification test for sensibility testing in patients with neurological problems in the hand. Moore [127] used the test to determine the effect of latex gloves on active haptic sensing, and found no significant effect. He did, however, find some effect in the area of tactility.

3.5. Tactility

Tactility differs from active haptic sensing in that it uses cutaneous cues only, and not muscular cues. It is passive, and involves stimulation of nerve endings. It is therefore more easily affected by a thin covering such as a medical glove, which might not significantly impede muscular activity. A number of different tests, covering various aspects of tactility, are reviewed in this section. They are listed in Table 5.

Table 5. Tactility Tests

Test	Primary Ref.	Other Refs.	Performance Tested	Apparatus
Roughness Discrimination Test	[137]	[64, 83]	Roughness discrimination	
Sponge and glue	[53]		Tactility/Haptic sensing	Figure A 28
Correx dynamometer	[74]		Pressure threshold	Figure A 29
Semmes-Weinstein Monofilaments/ Weinstein Enhanced Sensory Test (WEST)	[138]	[56, 72, 127, 139]	Pressure threshold	Figure A 30
2-point discriminator test	[140]	[56, 72, 102]	Tactile spatial acuity	Figure A 31
Force scaling and discrimination	[40]		Ability to discriminate forces	Figure A 32

The Roughness Discrimination Test [137] involves running a fingertip across small squares of sandpaper whilst blindfolded, and determining the “odd one out” on cards containing four squares. As discussed in Section 2.6.2, the test did not show significant differences between gloves in two studies [64, 75], although one showed a perceived difference. Further work is needed to identify whether the test has sufficient resolution to identify differences in the effect on tactility of medical gloves.

Texture identification could also be considered to include active haptic sensing in most cases, since the finger is not passive. Another texture identification test is the sponge and glue test used by Gnaneswaran et al. [53]. They found that glove type had a significant effect on the ability to identify glue lumps on a sponge. However, the test procedure does not appear to be well designed, in that the glue impressions were not at all randomised in size or location, so that after only a few rows, subjects would know almost exactly where to expect them. This seems highly likely to have influenced the scores, and most probably accounts for the fact that scores were higher with latex powdered gloves than with bare hands. However, the fact that significant differences were found is promising, and the test could hopefully be better designed so as to avoid these problems.

The tactile element involved here is the deformation of soft tissues in the fingertips and the subsequent stimulation of mechanoreceptors, which send pressure and deformation dependent signals to the brain, which is able to interpret this in terms of the geometry of the surface. Pressure sensitivity and the effect of gloves can be determined through pressure threshold testing. This generally involves applying an increasing force to the fingertip until the subject registers a sensation (which, in theory, is the point at which nerve endings fire and a signal is sent to the brain). The extent to which gloves block these tactile cues and reduce deformation of the fingertips can thus be estimated. A simple pressure threshold test can be performed using a Correx dynamometer, as per Neiburger [74]. He found that dentists wearing latex gloves had a 52% higher pressure threshold than those not wearing gloves. The individual effects of glove material, fit and thickness would be interesting to investigate.

A more commonly used pressure threshold test is the Semmes-Weinstein Monofilaments Test [138], or its variant, the Weinstein Enhanced Sensory Test [141]. In the 1800s, German physiologist Max von Frey designed a test in which hairs of different diameters were pressed into the skin of the subject's finger or thumb until the hair buckled. Each hair has a given buckling load and hence the force applied to the subject is consistent, whatever the force applied by the investigator. The minimum load (i.e. the smallest hair) at which the hair is detected by the subject is recorded. Semmes and Weinstein adapted the test to use a set of nylon monofilaments, which can be designed much more accurately in terms of buckling load. The advantage of this test over the Correx dynamometer is that the force is increased in discrete amounts, so that the test is not affected by the speed of application or reaction time.

Because of concerns over manufacturing accuracy and durability, among other things, the test was later developed into the Weinstein Enhanced Sensory Test, which has a number of advantages in terms of accuracy (see [141]). The filaments are individually force calibrated as opposed to just being made to given dimensions, and the ends are rounded, which prevents inconsistent stimulation of the FA I and SA I mechanoreceptors by the edge of the filament, and is also claimed to prevent "overshoot", where the applied force exceeds the characteristic force. This claim is somewhat spurious, as the overshoot is a dynamic effect, caused by applying the load too quickly, before the compressive wave generated by the contact has made a "round-trip journey" along the filament (see [142]). A more likely effect of the rounded end is to make a consistent end condition for buckling. The buckling force of a column is highly dependent on its end condition, and whether the end is held by friction and acts as "pinned", or is able to slide and acts as "free", can change the applied force by up to sixteen times.

The WEST is also designed to protect the thinner filaments from damage. Rather than individual handles for each monofilament, the apparatus consists of the WEST-hand™ and the WEST-foot™, with each device having one handle with multiple filaments, which can be rotated to present the required filament. It does have the disadvantage, however, of having only five filaments on each of the hand and foot devices, as opposed to the twenty in the full Semmes-Weinstein Monofilaments set. Since resolution is a key factor in medical glove testing, this makes the separate monofilaments more desirable for the purposes of this study. Furthermore, testing [143] has shown the monofilaments to be “a controlled, objective, reproducible force stimulus”, particularly if the same monofilament set and operator are used.

Moore [127] found that WEST showed an increased pressure threshold for latex gloves compared to bare hands. Shih et al. [56], using Semmes-Weinstein Monofilaments, found a discernible increase in the pressure threshold with the number of layers of latex glove worn. However, Tiefenthaler et al. [72] found that, while pressure threshold increased significantly from ungloved to gloved, there was no significant difference between vinyl first-aid gloves and sterile latex surgical gloves.

A commonly used tactility test is the two-point discrimination test [140]. This comes in various forms, including the “Disk-criminator”, the V-block, and a micrometer-type instrument, but they all work in a very similar way. Two points (or knife-edges in the case of the v-block) are applied to the fingertip at an increasing distance from one another until the subject indicates that they feel two points rather than one. A number of studies have attempted to use two-point discrimination as a comparison tool between gloves. However, the problem with this is that two-point discrimination essentially tests “innervation density” i.e. the spacing between nerve endings on the contact surface (usually the fingertip). If the distance between the points is less than the distance between two adjacent nerve endings, it will feel as if only one point is being applied. Being purely a property of the fingertip, two-point discrimination should not therefore be affected by the wearing of gloves, especially thin gloves which do not significantly affect force distribution. Shih et al. [56] tested the thumb and index finger with varying numbers of latex gloves on, and found that a significant difference only existed on the thumb, and only for two and three layers of gloves. This might be where the elasticity of the gloves starts to have an effect, and the interaction of the layers could also be a factor, with forces not being transmitted through homogenous material and discrimination being distorted. Tiefenthaler et al. [72] found no significant difference in two-point discrimination when wearing vinyl first-aid gloves, sterile latex surgical gloves or no gloves. It is not considered that this test is worth pursuing, since it does not test any effect caused by the wearing of medical gloves.

Finally, Wheat et al. [40] tested human ability to scale and discriminate normal and tangential forces, such as would be experienced in grasping. While their aim was to show that cutaneous afferents (sensory nerves) provide precise information about grasping forces, the apparatus could be used to test how gloves affect this ability. This information complements Westling and Johansson's tests [28, 30] in that the effect of gloves on the sensory elements of grasping can be separated from the effect on motor response and surface characteristics.

3.6. Medical Application

The vast majority of tests involving actual medical procedures are based in dentistry and have been designed in order to compare gloves, perhaps because dentists have to wear poorly-fitting examination gloves for intricate procedures and thus are keener to improve glove design. Some tests have also been carried trialled by nursing researchers. These tests generally assess dexterity, but some include elements of tactility. The medical application tests reviewed here are listed in Table 6.

Table 6. Medical Application Tests

Test/Procedure	**Primary Ref.**	**Other Refs.**	**Apparatus**
Scaling of typodonts	[81]		Figure A 33
Dental student skill acquisition analysis	[63]		
Roughness Discrimination with explorer	[76]		
Dental pin placement	[82]		
Enlarging canal	[82]		
Bur block test	[74]		Figure A 34
Endodontic file test	[74]		Figure A 35
Multiple Orthodontic Procedures & Questionnaire	[92]		
Dressing preparation	[83]		
Syringe water drawing	[83]	[53]	
Suture test	[53]		

Uldricks et al. [81] measured the effect of surgical gloves on the ability of dental students to remove artificial calculus from a *typodont*. They found no significant difference in remaining calculus deposits between students who wore surgical gloves and those who did not. Brantley et al. [63] studied first-year dental students during an operative dentistry preclinical technique course, randomly selecting half the students to use latex surgical gloves for the entirety of the course, while the other half wore none. They found that wearing the gloves had no significant impact on practical examination performance or speed.

Wilson et al. [76] adapted Nolan and Morris's Roughness Discrimination Test [137] for use with a dental explorer (a probe used to detect tooth decay). They compared tactile sensitivity when wearing latex gloves with that of bare hands, and found no significant difference. Interestingly, perception tests carried out at the same time found that 62.5% of participants believed that the gloves affected their ability to discriminate accurately. It is not clear whether the perceived effect documented by Wilson et al. was due to psychological effects or whether the test is not sensitive enough to pick up the differences. Interestingly, identifying calculus (tartar) and caries (decay) was one of the tasks mentioned in initial discussions with dentists as being perceived to be more difficult with gloves, especially for dental students. Further adaptations of the test and fine-tuning of the variation in sandpaper grade might yield better results.

Hardison et al. [82] compared gloved and ungloved performance of qualified dentists in two tasks: placing a pin as part of a restoration, and enlarging a canal. They found no significant difference in either speed or quality of work. Since the procedures require dental experience, they would be difficult to simulate in tests with untrained participants.

Chua and Bagg [92] tested dentists carrying out actual procedures on real patients. While this has the advantage of realistic conditions and tasks, the variables that can be tested are somewhat limited. They carried out water-leak puncture tests and the subjects filled out perception surveys. While this produced differences in results between different types of gloves, only the puncture resistance could be empirically tested. The perceived difference in working speed produced by different gloves, for example, was not objectively verified. This kind of testing has its place, but must be coupled with quantifiable and repeatable tests.

Two simpler, but still relevant, tests were carried out by Neiburger [74] on fifty dentists. The bur block test is very similar to some of the pegboard tests, but uses actual dental equipment. Neiburger does not analyse the statistical significance of the result, but he found only a 4.2 percent increase in the time taken for the test using gloves, which is less than the difference between left- and right-handed participants, suggesting it is not necessarily an indicator of anything. It is not clear how the time to move the bur was measured, but it is considered that inaccuracies in timing are likely to be fairly significant when measuring one movement which takes approximately two seconds. The test might benefit from being lengthened. The second test consisted of putting a rubber stop onto an endodontic file. Neiburger found a much greater difference in the results of gloved and ungloved participants. The time taken to complete the task was 13 per cent greater with gloves than without, and the number of finger punctures was eight times greater with gloves than without. This is a promising test which could easily be repeated with non-dentists.

Norton and Hignett [83] also designed two simple tests which replicate tasks carried out on a regular basis by practitioners. The first is a dressing preparation task, in which the subject must open a dressing pack, remove pieces of gauze with tweezers and place them in marked squares, and then cut pieces of tape and stick them onto marked rectangles. In the second test, the subject must open a sealed bottle of water, draw out a given amount of water in a syringe, and reseal the bottle. They did not present an analysis of the test method or the results, so it is difficult to ascertain the usefulness of the tests. Gnaneswaran et al. [53] carried out a similar test where water was drawn from a bowl into a syringe and ejected again. Since they used two glove materials, each having a powdered and non-powdered condition, their analysis was somewhat convoluted, involving two different factorial methods in order to separate the effects of glove material and powder. The first analysis found no significant effect of gloves when the four conditions (and the ungloved condition) were separated, but they found a significant difference in the time taken using latex and vinyl gloves (being greater with latex gloves) when the powdered and non-powdered conditions were grouped. The discrepancy is not commented on, and it is therefore difficult to place confidence in the significance of the results. Another test they carried out was the suture test, in which subjects were required to stitch a circular pattern on a plastic sheet, and the completion time measured. They also found a significant glove effect for this test.

3.7. Other

A number of tests that do not fit under any of the previous headings, but are relevant to glove design, are listed in Table 7.

Table 7. Other Tests

Test	Primary Ref.	Parameter	Apparatus
Plate indentor	[144]	Adhesion, hardness	Figure A 36
Contact angle measurement	[119]	Hydrophilicity	Figure A 37
Fit evaluation	[98]	Fit	

The plate indentor [144] can be used to measure adhesion characteristics of different rubbers. A plate with a cylindrical indenting edge is pressed into a sheet of rubber at a constant rate and the indentation force measured. Information about the frictional properties of the rubber can then be inferred. While this may help in understanding variation in glove frictional properties, simpler and cheaper tests can be performed which will provide more relevant information on friction behaviour.

A further test which could be of some use is *contact angle* measurement, which determines hydrophilicity (the tendency of a surface to be wetted by water) by measuring the *contact angle* of a water droplet on the surface. This is a measure of how well lubricated the contact becomes when wet and hence how much the coefficient of friction is reduced compared to the dry state. This could be a key test as many performance differences between gloves when wet have often been noted (e.g. [145]).

Roberts [119] measured the *contact angle* by dispensing a known volume of water from a microsyringe onto the surface and measuring the drop diameter under a microscope. More complex methods involve a *contact angle* goniometer, which uses cameras and software to capture the droplet shape.

3.7.1. Fit tests

A number of the test results so far have suggested that glove fit could play an important part in performance. However, in order to measure its effect, “fit” needs to be quantified in some meaningful way, and it is highly likely that it cannot be adequately described by a single number. A few have tried, usually based around volume. However, the most detailed analysis has been done by Tremblay-Lutter and Weihrer [98]. They measured key glove and hand dimensions – finger lengths and girths, palm girth, total volume – and compared them to produce “ease” values for each dimension. (Inner glove dimensions were estimated based on outer dimensions and glove thickness.) They found that changing the size between small, medium, large and extra-large produced significant differences in ease. Further to this, they carried out a number of dexterity tests and followed these with questionnaires to ascertain both the objective and subjective ‘optimal ease’.

There were significant differences in all tests due to hand condition, some more dramatic than others. The best performance was achieved using the gloves selected as best fitting and the smaller size. Performance was significantly worse with the larger gloves. Objective and subjective results agreed well. Both were combined to produce the optimal ease value for each dimension (digit length, digit girth and palm girth) with the values for the digits averaged across the five. They found much less consistency in the digit girth ease than the other two. The smaller dimension possibly produced greater inaccuracy in the thickness assumption. It was also suggested that the amount of strain might have affected the thickness.

3.8. Conclusions

3.8.1. Grasping

Maximal exertion tasks such as the hand dynamometer are not very useful for comparing gloves, since they depend more on physical strength than glove properties, particularly with thin gloves. Sub-maximal tasks are more useful for measuring the frictional properties of the glove. Of these, **Westling and Johansson's pinch grip rig** is the most promising. It can give information about both frictional properties of the glove and the psychological effect on grip of the loss of tactility caused by gloves, and it appears to have some potential for differentiating between medical gloves. The test can also be modified to allow video monitoring of fingertips during gripping.

3.8.2. Pure Friction

Most of the tests involve too much human interaction to be reliable, either in the application of force (UoS rig) or in the measurement (Polyco rig). Most also measure dynamic friction, which is only relevant to a few tasks such as orthodontic wire bending and endoscopy. Most tasks involve tool-holding, which relies on static friction. The most promising test for static friction uses the **Westling-Johansson rig**.

3.8.3. Dexterity

The most promising varieties of pegboard test are the **O'Connor Finger Dexterity Test** (which was found by two studies to give good discrimination between gloves) and the **Purdue Assembly Test** (which showed discrimination between both glove type and thickness). The **Pennsylvania Bi-Manual Workpiece Assembly Test (PBWAT)** was also found to discriminate well. The **Crawford 'Pins and Collars' Test** is the best tweezer test available. Other useful hand-tool dexterity tests include the **Bennett Test**.

Other useful dexterity tests are **knot-tying tests**, which apply to all surgery; the **Coin Rotation Test**, which could be modified to use surgical tools; and the **paper shape cutting test**, which showed significant differences between latex and vinyl gloves.

3.8.4. Active Haptic Sensing

Lederman and Klatzky's haptic identification of common objects, Nelson and Mital's pipe diameter identification and the Shape/Texture Identification test all showed some promise for measuring glove effect on haptic ability, but require further development.

3.8.5. Tactility

Of the theoretical tactility tests, the pressure threshold tests were thought to be more useful than the two-point discriminator, which is unlikely to be affected by glove thickness. The **WEST** is preferable, but the **Correx dynamometer** is a cheaper alternative. The **force scaling** could give some interesting results, but the rig is expensive. In terms of more applied tests, both the **roughness discrimination** and the **sponge-and-glue test** could be useful with some modifications.

3.8.6. Medical Application

The **Roughness Discrimination Test with a dental explorer** showed a perceived difference in performance, but no measured difference. Some fine-tuning of the test procedure might yield better results.

Putting a stop on an endodontic file was found to discriminate well between gloves in terms of time taken and number of punctures.. It is a very simple test and may therefore be worth trying.

Norton and Hignett's nursing tests show potential. Gnaneswaran et al. [53] found a significant difference between latex and vinyl gloves when carrying out a similar syringe task. Their **suturing test** also found a significant effect and obviously simulates a common medical task.

3.8.7. Other tests

Both hydrophilicity and fit are considered to be important factors in glove performance, and so Tremblay-Lutter and Weihrer's **fit evaluation** and **contact angle measurement** are worthwhile tests for medical gloves.

3.8.8. Focusing and developing the tests

So far, the analysis of the tests has been almost entirely based on their ability to discriminate between hand conditions (gloved and ungloved, latex and nitrile etc.). However, to fully consider the usefulness of the tests and determine which to further develop, and where new tests are needed, their relevance to medical practice needs to be assessed. This will be dealt with in Chapter 4. In Chapter 5, the tests will be analysed based on the findings of the previous two chapters, and a number of tests selected for further development and medical glove testing.

4. Interviews

In order to concentrate research on the areas of greatest need and to design tests that are useful and realistic simulations of medical practice, it was necessary to gather data from practitioners. It was decided that the best way to do this was through semi-structured interviews.

As well as gathering information on the participants' roles, disciplines and glove use, a series of open-ended questions were used to identify the tasks believed by users to require most dexterity and tactility, and those most affected by glove performance, as well as any other issues related to gloves that might aid the study. It was decided that the study would take place within Sheffield Teaching Hospitals NHS Foundation Trust (STH) as this was most accessible to The University of Sheffield.

4.1. Ethical Review Process

In order to carry out research involving NHS staff, ethical approval of the study by the local Research Ethics Committee (REC) was required. The review process is illustrated in Figure 4.

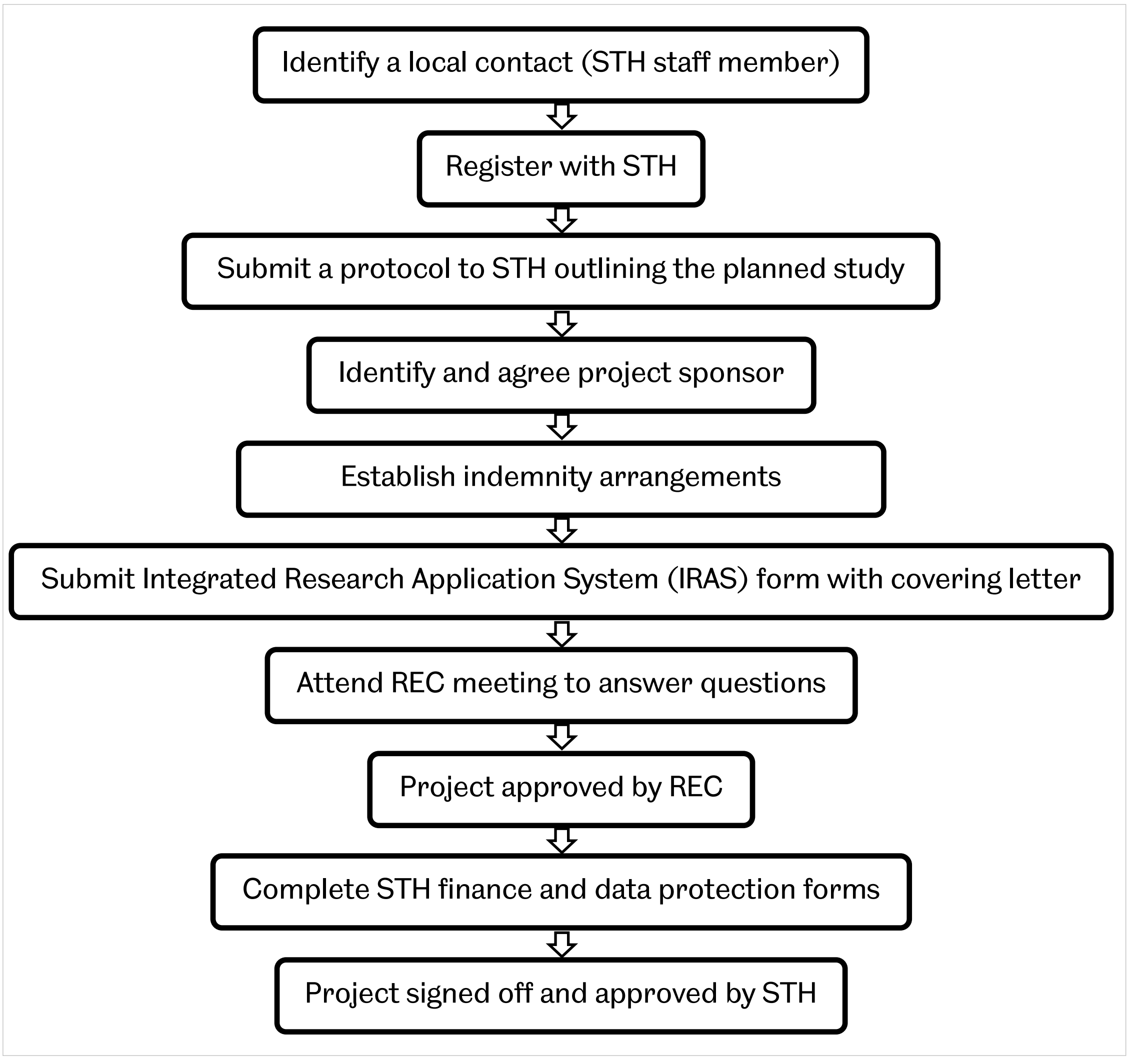

Figure 4. NHS ethical review process

The protocol included: background to and aims of the study; methodology; participant recruitment; a Gantt chart of the project as a whole; ethical issues; costing, and researcher expertise.

Application to the Research Ethics Committee (REC) was via the online Integrated Research Application System (IRAS). The form required similar, but extended information, and also included details of, for example: scientific justification, informed consent, data processing and storage. Included with it were: the participant information sheet, the invitation email text, the consent form, and the interview guide (see Appendix B). The whole ethical approval process took around six months.

4.2. Procedure

It was decided that the interviews should be on a one-to-one basis. Group discussions were considered, but it was felt that simultaneously drawing together a group of participants, many of whom would be consultants and other senior staff, would be very difficult, and would require each participant to take a larger amount of time out of their day, thus making them less likely to agree to participate. Individual interviews also ensured, as much as possible, that answers were not affected by those of others, and that participants were free to consider the questions for themselves and to freely express the tasks that they found most difficult. Experience at BM Polyco Ltd. suggested that user preference in gloves is affected by the opinion of other practitioners. The questions were designed to be sufficiently open-ended that the participant was not led down one particular line of thought, but also included prompts where information was not forthcoming. With a wide enough selection of participants, it was hoped that a consensus would be formed in at least some of the areas, which would enable judgments to be made on the most productive direction for the research.

Participants were approached by email through the STH local contact, and interviews were conducted at their place of work. For some of the consultants and surgeons, this had to be between operations or appointments. The duration of the interviews varied between six and twenty-eight minutes. Audio from the interviews was recorded, and transcribed at a later date. It was originally intended to follow up the interviews with sessions in the Clinical Skills Laboratory, in which participants demonstrated some of the more difficult tasks that they had described in the interviews, in order to aid in test design, as well as to identify particular issues with gloves that could not be determined from the interviews. However, it was found that demonstrations of the tasks could be obtained from other sources such as online videos, and due to the practical difficulties involved in organising the sessions, it was decided not to pursue this approach.

4.3. Participants

It was desirable to include participants from a range of disciplines and roles, so that there was a better chance of determining the particular areas where the use of gloves causes difficulty. It was also desirable to have a range of experience in the practitioners, as those with a lot of experience may have different issues with gloves, and find different tasks harder. Preference for glove type was also expected to vary, as it was thought that the conditions in which practitioners train have an effect on their future preference.

The sample size and disciplines to be included were decided in conjunction with the STH local contact, a consultant general surgeon. It was planned to include approximately forty-four participants from six disciplines, but as interviews were conducted, it was recognised that certain disciplines, such as Orthopaedics, yielded much more information and a greater variety of answers, whereas some, such as Anaesthetics, duplicated answers. For the latter, it was not considered worthwhile to recruit the full quota of participants. Discussion also revealed other disciplines that had not been considered and should be included. 35 medical practitioners were eventually interviewed. Table 8 shows a breakdown of the participants by discipline and position.

Table 8. Breakdown of interview participants

Discipline	Consultants	Registrars	SHO’s	Nurses/ODP’s
General Surgery (Colorectal)	3	2		2
Cardiology		1		
Orthopaedics	5	1	1	2
Ophthalmology	1	2		
Urogynaecology	1	1		
Dentistry	2	2		1
Anaesthetics	3			1
Phlebotomy				1
Transplant	1			
Emergency	1			
Ear, Nose and Throat	1			

4.4. Results

The guide used during the interviews can be found in Appendix B. Participants were asked about:

- their examination glove use (4.4.1) and surgical glove use (4.4.2) – frequency, current type(s) used, preferences, activities for which they are used, grasp types used (Cutkosky’s taxonomy of grasp types [29] was used as a guide – see Figure 3)
- tasks requiring most manual dexterity, tactile sensation and hand fatigue and those most affected by wearing gloves (4.4.3)
- tasks most likely to cause tearing (4.4.5)
- what they considered to be the main issues with glove use (4.4.6)
- their perception of how various glove properties affect performance (4.4.7 - 4.4.10)
- special precautions regarding glove use when risk of infection is high (4.4.11)

- other issues or incidents that would be helpful to know (4.4.12)

Results are displayed in terms of percentage of users who gave the response. However, it should be noted that due to the informal nature of the interviews, not every participant answered every question, and some responses covered a number of points. Therefore, the percentages will not add up to one hundred, but the bar charts give an idea of the relative frequency and importance of responses.

4.4.1. Examination gloves

Examination gloves were used for a variety of tasks including: performing examinations; using power tools such as a dental hand-piece (e.g. for drilling) and precision tools such as forceps (e.g. for removing stitches); taking blood and cannulating (Figure 5); applying dressings; and cleaning. A broad range of grasps were used, particularly precision prismatic grasps (see Figure 3). Most users found it difficult to define exact grasps, particularly in relation to Cutkosky's diagram, so exact numbers were hard to obtain.

Figure 5. Venous cannulation (reproduced from [146])

Thirty-four of the thirty-five participants used examination gloves regularly, usually multiple pairs daily. All of those used Schottlander™ Latex-Free Flexible Nitrile gloves within STH as were mandated by the Trust, although many had previous experience of latex or copolymer gloves (a blend of two polymers, such as polyethylene and ethylene butyl acrylate – see Figure 6). Only the ophthalmic surgeon did not use them at all. Some also used Bodyguards® Sterile Blue Nitrile Exam Gloves for sterile dressings, and some used Kimberly Clark ® Sterling ® Nitrile Gloves at another Trust.

Figure 6. Copolymer medical glove (reproduced from [147])

Figure 7 shows user opinions on the comparison between examination glove materials. Almost half of participants expressed a preference for previously used latex examination gloves over the current nitrile ones, with many saying that latex fitted or conformed better. Easier donning, better comfort and roughness were also given as reasons for the preference.

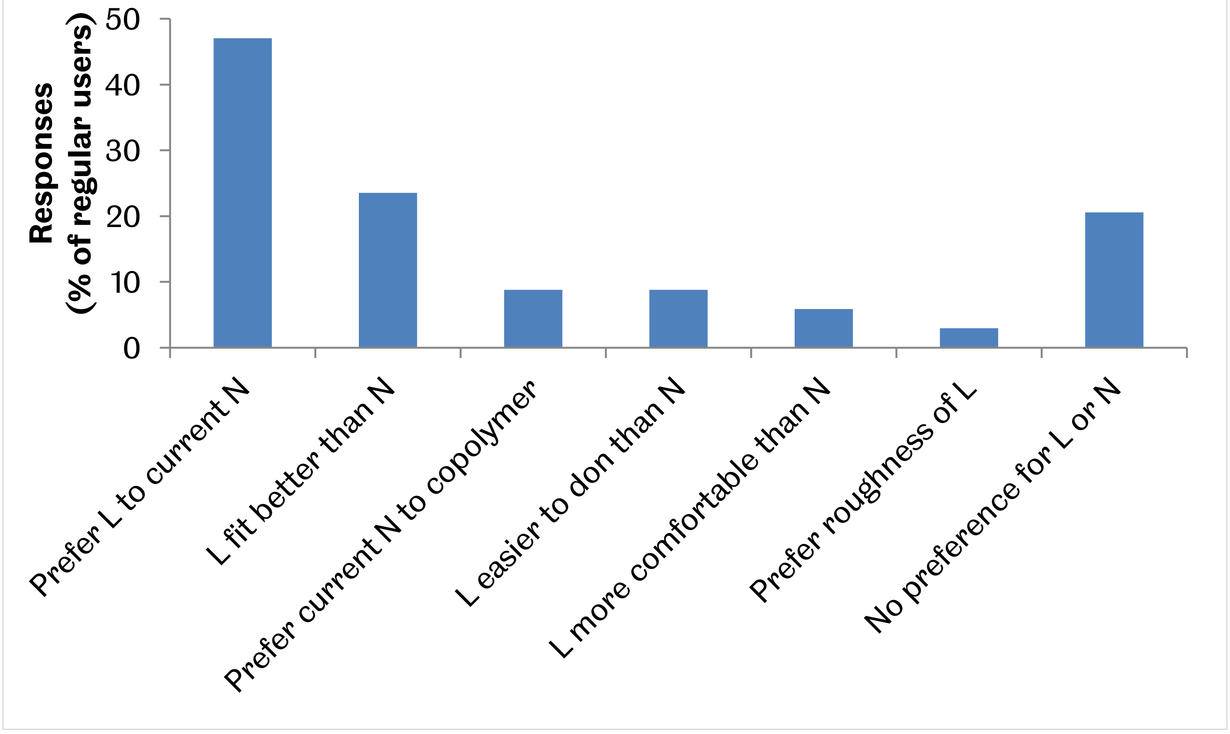

Figure 7. Examination glove preferences (L = natural rubber latex, N = nitrile), from 34 regular examination glove users

Fit of the currently-used nitrile gloves was identified as a problem by almost one third of regular glove users, and was followed by elasticity, with loss of tactility and difficulty with donning also common issues.

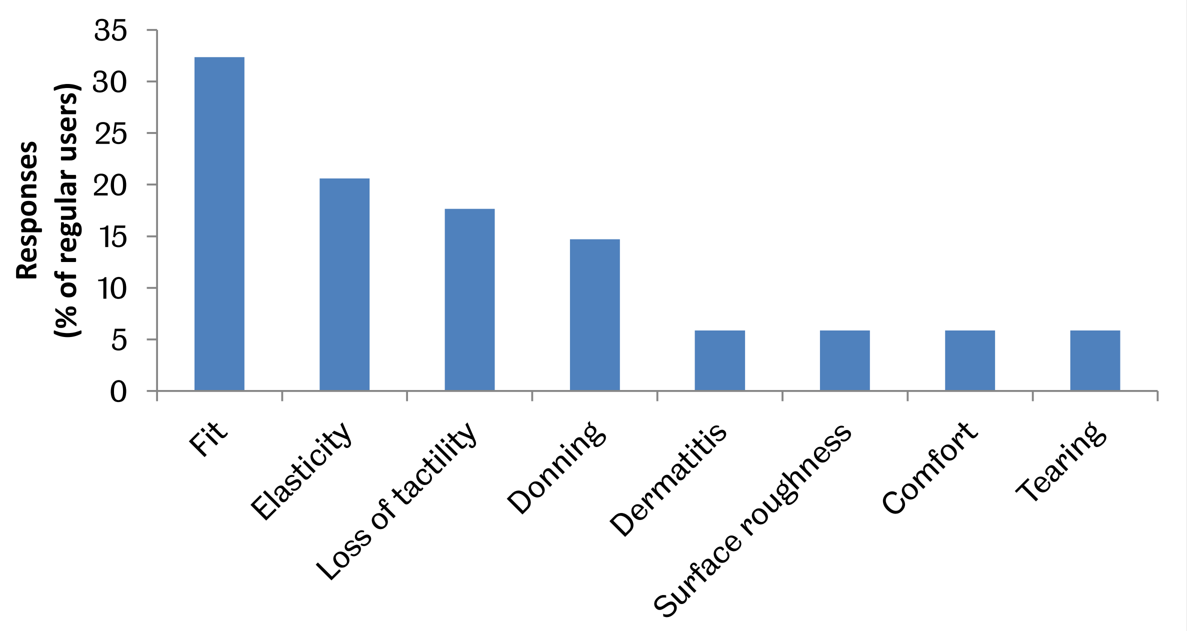

Figure 8. Issues with current nitrile examination gloves, from 34 regular examination glove users

Figure 9 shows the interaction of responses, the area of each circle being proportional to the number of responses that fitted that group, and the overlapping areas representing those whose response fitted more than one group.

A number of users identified fit and elasticity together as problems with nitrile gloves, suggesting a perceived link between the two. All of those participants were amongst those who felt that latex, a more elastic material, fitted or conformed better. Poor fit was also thought to be due to mismatching of glove and hand dimensions and ratios. Loss of dexterity and tactile sensation were identified as the main effects of poor fit.

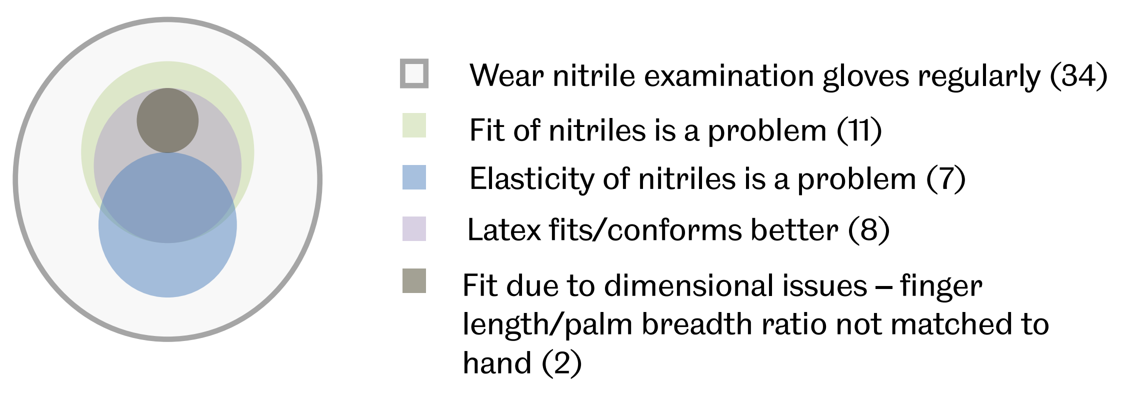

Figure 9. Venn diagram of fit-related responses (no. of responses in brackets)

4.4.2.Surgical gloves

Surgical gloves were used less regularly, but usually a few times a week. Dentists and non-theatre nurses tended to use them less than once a week or not at all. Most used Biogel ® standard latex gloves. Orthopaedic surgeons also used indicator under-gloves (green-coloured gloves that help to identify punctures in surgical gloves), except for hand surgery. Some general and orthopaedic surgeons also used a latex glove with a nitrile coating. Ophthalmologists used Biogel® M, a microsurgery latex glove, and two participants used Biogel® Super-Sensitive – a thinner glove. Non-latex options included polychloroprene (neoprene) and polyisoprene, but these were generally used only in cases of known patient or surgeon allergy.

None of those who used surgical gloves expressed a desire to change (except for reasons of allergy), with the majority explicitly stating that they were happy with Biogel®. Some mentioned reasons for this such as comfort, tear resistance, fit, sensitivity and flexibility. There was, though, a general openness to alternatives if it saved money, provided they were of equivalent or better quality.

Eight participants had used latex alternatives and six mentioned using non-latex alternatives. All of those preferred Biogel® except one who could not remember a difference. Complaints for latex alternatives included feeling thicker (although they were not), less sensitive, less comfortable and flexible, not fitting as well and being more slippery; the non-latex gloves were perceived to be “stiffer” and therefore less sensitive, slippery and hard to don, but primarily that they did not “feel right” or the “handling” was not as nice. Most participants chose not to wear the Super-Sensitive gloves because they either tore more or caused them to worry about tearing.

Tasks carried out using surgical gloves were generally more dextrous and specific to the specialty, varying from microsurgery in the eye with delicate hand tools to using power tools and bone mallets in orthopaedics. Common tasks included incision with a scalpel, retracting, instrument and tissue handling, suturing and knot-tying.

4.4.3.Tasks

The tasks most commonly identified by practitioners as being adversely affected by gloves involved feeling blood vessels: cannulating (Figure 5), injections, taking blood or measuring a pulse. Knot tying and suturing, handling syringes and vials, using adhesive tape or dressings and per rectal examination were also common. The requirements of these tasks include fine dexterity such as manipulating tools and small objects, and tactility such as the identification of surface irregularities with fingertips. A comment made by seven participants was that you get used to wearing the gloves and adapt your technique, or your brain modifies the way it interprets sensory information to compensate for the gloves.

Other tasks identified as requiring manual dexterity include surgical approach (using a scalpel), manipulating prostheses and fractures, *laparoscopic surgery* and endoscopy. The required dexterity ranges from very fine (e.g. using an ophthalmic chopper to manipulate the lens of an eye during cataract surgery) to coarse (removing Ilizarov frames with spanners).

Tactility was commonly linked to dexterity in terms of feedback when manipulating tools (e.g. dental handpiece, orthopaedic power tools). Other tasks identified as requiring tactility included feeling soft tissue properties (tension, lesions) and fracture fragments, and applying Vacuum Assisted Closure® (VAC) dressings.

4.4.4. Hand fatigue

Figure 10 shows the categories of response given relating to hand fatigue, and the percentage of participants whose response fitted each category.

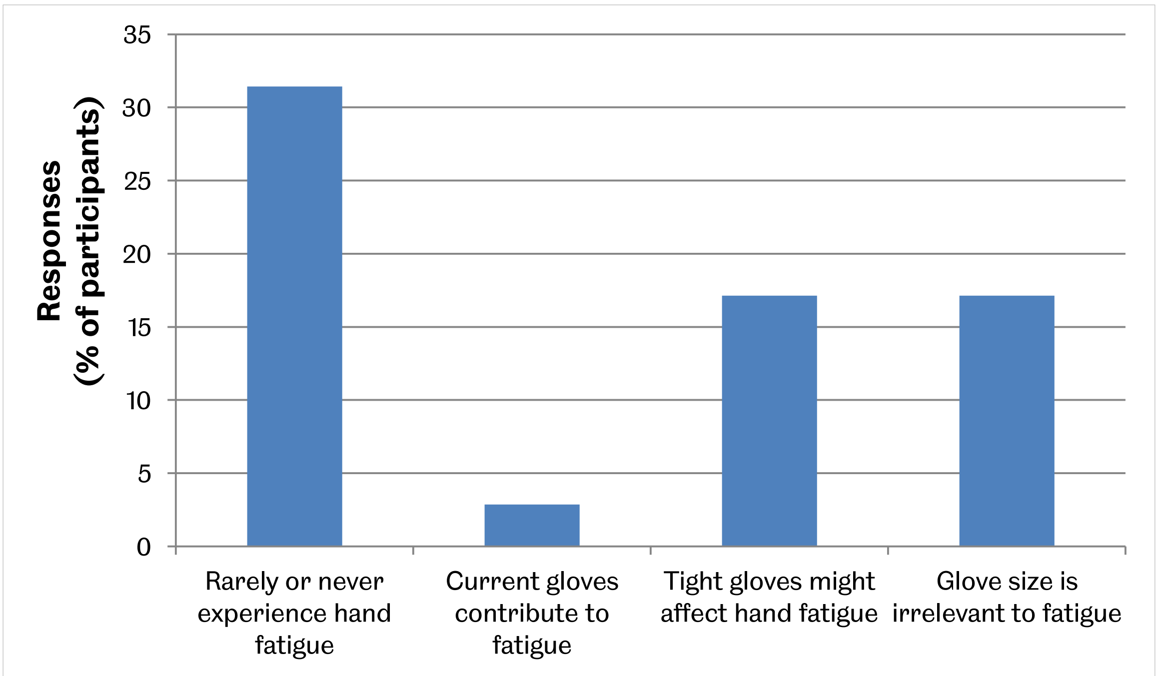

Figure 10. Responses on hand fatigue (from 35 participants)

While some participants thought that glove size or even type contributed to fatigue, others thought that fatigue was due to the physical exertion, the length of time, or the position involved. One ophthalmologist said that stress could be a factor in fatigue, causing you to grip more tightly, and that reducing fatigue was down to technique, and learning to relax.

The most common tasks that were mentioned as causing hand fatigue were *laparoscopic surgery*, retracting, using rotating, trigger-operated tools (dentists and orthopaedic surgeons) and suturing.

4.4.5. Tearing

By far the most common reason given for tearing was donning, especially if hands are not completely dry. The increase in friction with damp hands means that excessive force is required to pull them on, often causing the cuff to break. Orthopaedic surgeons, who double-glove because tearing is a particular issue for them, found bone fragments to be the most common cause, while two colorectal surgeons also found cutting or piercing of the non-dominant hand during suturing or cutting to be fairly common. Sterile gloves were perceived by some participants to tear more than examination gloves.

4.4.6. Main issues with glove use

Figure 11 shows the most common responses to the question, “What are the main issues with glove use?”

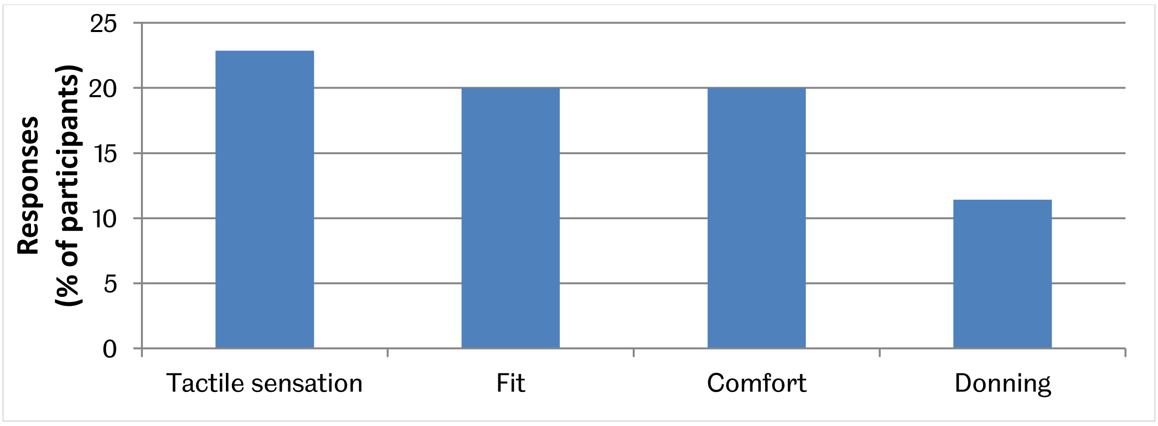

Figure 11. Most common responses to the question, "What are the main issues with glove use?" from 35 participants

The main issue with glove use was most commonly identified as tactile sensation. Gloves were thought to reduce sensation, particularly when fit was poor. Some participants said that if gloves gave the same sensation as bare hands, they would be more likely to wear them for certain tasks such as cannulating. Fit was often mentioned – either the importance of it in terms of performance, the poor fit of the nitrile gloves due to lack of flexibility, wrongly dimensioned gloves or manufacturing variations.

Comfort of the gloves, most often related to sweating and clamminess, was an equally common response. A number of people thought that donning was the main issue, with most of those particularly focusing on donning when hands are not completely dry. The problem was not confined to examination gloves, but also included surgical and microsurgical gloves.

Other common issues included restriction of movement and poor flexibility of the nitrile exam gloves, and the need for better grip. Two participants said they would like the gloves to be both stronger (to give puncture resistance) and thinner (to give better tactile sensation and dexterity). Irritation of the skin, the lack of good alternatives to latex, the need to improve the indicator system, and problems with the Kevlar® safety gloves (used for puncture protection when there is a high risk of infection) were also mentioned.

4.4.7. Material effect on performance

Separately from the question on examination glove preferences, which was clearly dominated by material issues, participants were asked what effect they thought glove material had on their performance. Figure 12 shows their responses, as summarised in ten categories.

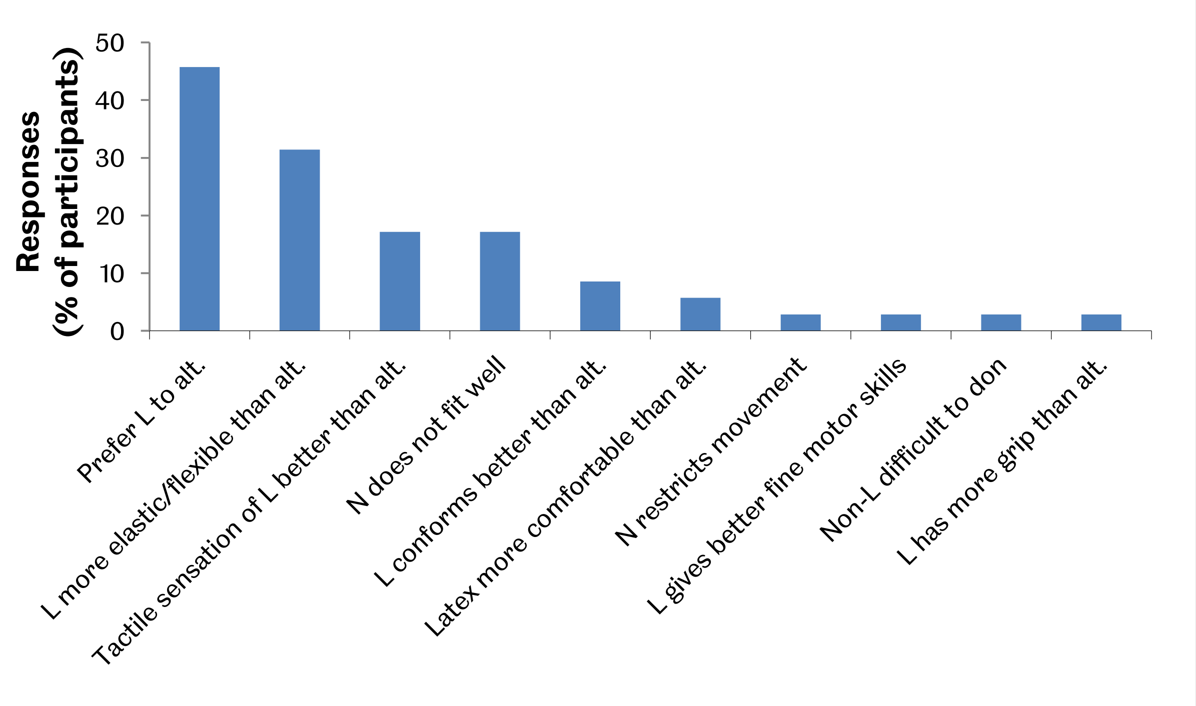

Figure 12. Perceived effect of material on performance (L = natural rubber latex, N = nitrile), from 35 respondants

Latex is clearly the preferred material amongst medical practitioners, and the responses suggest it is mainly due to better flexibility and conformability, which was perceived as fitting better. The main effect of this was thought to be on tactile sensation. Non-latex gloves were often perceived to be thicker even when they were not, and this was also thought to affect tactility.

In terms of material effect on performance, responses were mixed between those who thought it impacted performance and those who did not. Of those who thought it did, reasons included that the inelasticity of non-latex gloves, causing poor fit, made them unsafe, and that performance was slowed by needing to replace gloves that tear constantly. Of those that thought that material had no effect, many thought that adaptation to the gloves minimised any loss in performance.

4.4.8. Perceived effect of thickness

Thickness was linked by two-thirds of participants to *cutaneous sensibility* or feel, while fourteen per cent perceived an effect on dexterity. Many recognised that there was a trade-off between tear resistance and sensitivity, but the relative importance of each depended upon the role of the respondent. Two orthopaedic surgeons and two general surgeons said they would prioritise puncture resistance over sensitivity, while one dentist, the ENT surgeon and the transplant surgeon said the opposite. Worrying about tearing was also a factor as much as the problem of tearing itself.

A number of participants said that they chose not to wear the Super-Sensitive gloves, either because they tear, they worry about tearing, they did not perceive a performance increase, or they were too expensive. Only two participants did use them, and one of those only when double-gloving for intricate surgery.

While many participants linked glove thickness with *cutaneous sensibility* and dexterity, most were less able to define the specific effect of thickness on their performance. Their responses are shown in Figure 13. Of those that did respond, the majority felt that thickness had little or no effect on their actual performance.

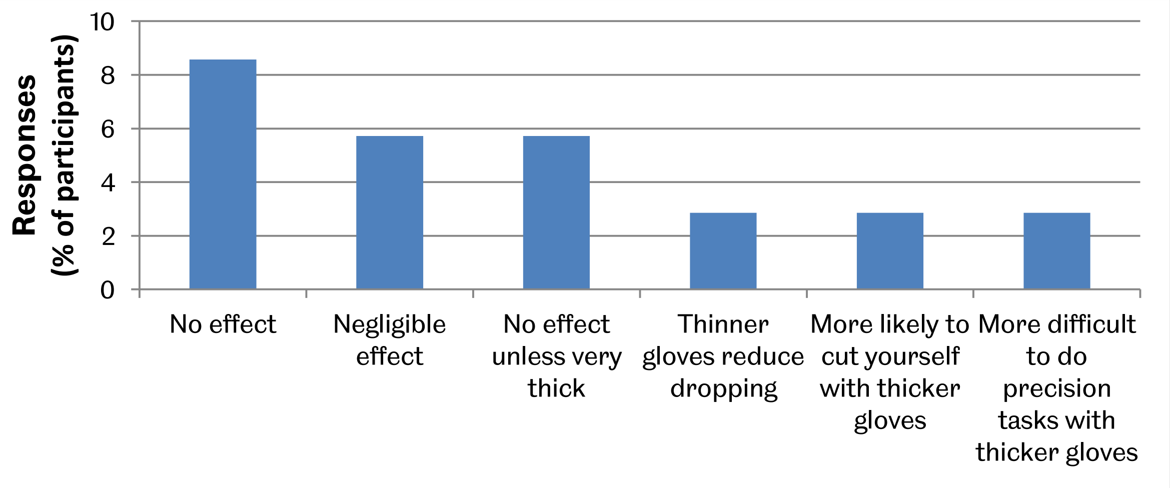

Figure 13. Perceived effect of glove thickness on performance (from 35 participants)

4.4.9. Perceived effect of grip pattern

Many medical gloves (including the examination gloves used by STH staff) have a raised pattern on the fingertips that aims to improve grip (see Figure 14). Those participants who showed more of an interest in discussing glove properties and their effects on performance were asked their opinions on the effects of the grip pattern.

Figure 14. Grip pattern on examination glove fingertips

The responses of the twenty-two participants who discussed grip pattern are shown in Figure 15.

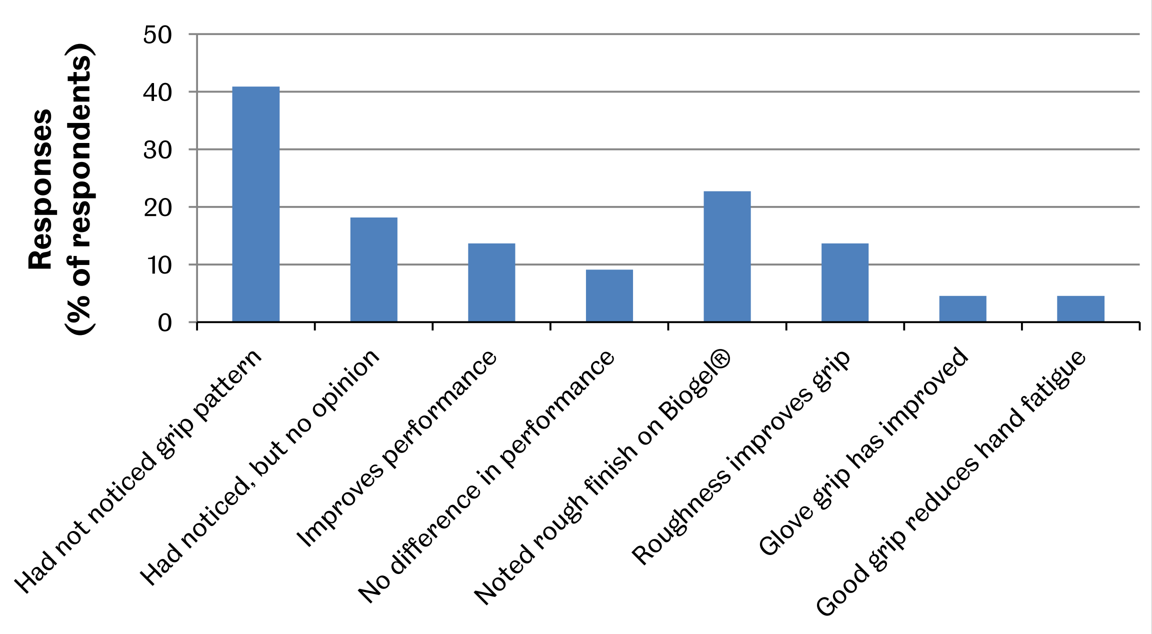

Figure 15. Perceived effect of grip pattern on performance (from 22 respondents)

Almost half of respondents had not even noticed the printed pattern on their examination gloves, and most did not have a clear idea of what the grip pattern was supposed to achieve. It was assumed, by those who had noticed it and those that had not, that the pattern was either to improve tactility or grip, and the perception of its success in either of those was mixed. The rough finish on Biogel® surgical gloves was noted by five respondents, with three of those believing that it improved grip.

4.4.10. Perceived effect of fit on performance

Oversized and undersized gloves produce different issues and so are treated separately. Figure 16 and Figure 17 show the perceived effects of oversized and undersized gloves respectively.

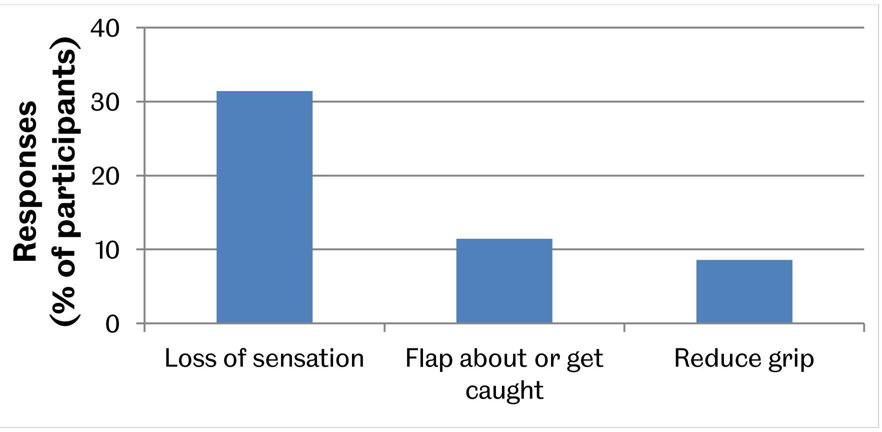

Figure 16. Effect of oversized gloves on performance

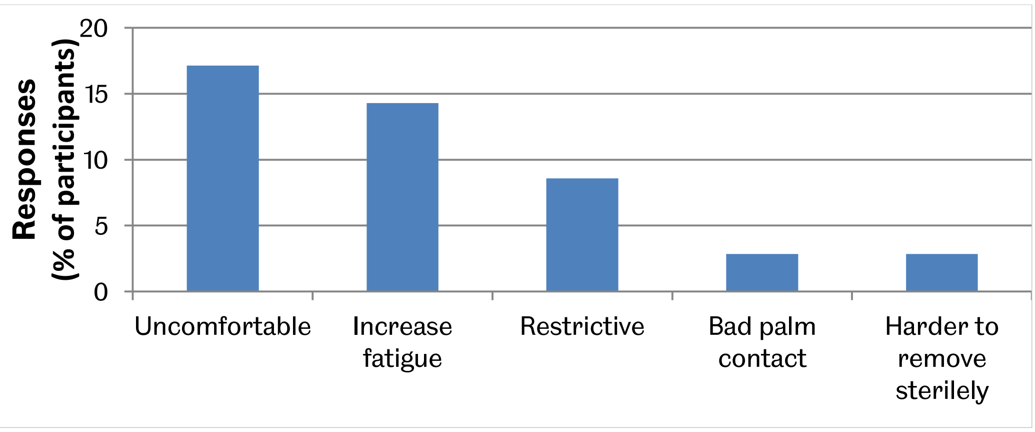

Figure 17. Effect of undersized gloves on performance

The most common comment on sizing was that in order to have the correct palm breadth, participants often had to use gloves where the finger length or breadth was not correct. For those who had short fingers, they were having to pull the gloves up regularly. On the whole, people had an issue with fingers being too loose or baggy, as opposed to palms, which people preferred to be loose to allow movement and palm contact. Four people specifically said that they preferred snug-fitting gloves or deliberately under-gloved (went down half a size) (two saying it was for better feel), while one said they wore loose gloves because their hands sweated less.

A number of people said that they were between sizes on the nitrile gloves, or that the gloves did not fit at all, and that the much larger range of surgical glove sizes made it easier to find a glove that fits and therefore to do fine tasks such as incising. Some participants also noted that they have to go up a size if their hands are not dry after scrubbing or at the end of a surgical list, when their hands have swelled.

4.4.11. Special precautions for situations with a high risk of infection

Seventeen people said that they double-gloved for high-risk patients – one wore indicator under-gloves. More than half of those commented that tactile sensation was worse. Theatre nurses said they also could not feel the temperature of water or pick up sutures. Other comments were that they were restrictive, made you feel clumsier, slowed you down or were uncomfortable or even painful (for one participant who found the gloves too small already). However, most said when asked that they could still perform the tasks they needed to. One participant said that he thought the loss of sensation was due to the movement between the layers inhibiting transmission of sensation, rather than the increased thickness, so that active touch was most affected.

All but one of the orthopaedic surgeons, who always double-glove in theatre, wear Kevlar® undergloves for high-risk patients. The hand surgeon used them once but found that they reduced sensation, making you too "clumsy", increasing the risk of injury, and said that good practice and not rushing is a better way to protect yourself. Other surgeons had also used them previously. Those that had used the Kevlar under-gloves were very critical of them, saying they were restrictive. However, most said that you could adapt and do most basic tasks even if it took longer, with only one saying it made suturing impossible.

Eleven people said they did not double-glove. Most said they always used "Universal Precautions", some commenting that they believed the loss of sensation caused by double-gloving increased the risk of injury, and that two layers were not enough to prevent injury anyway.

4.4.12. Miscellaneous comments

Because of the informal nature of the interviews, views on a number of other topics were recorded. These included: glove requirements; getting used to gloves; cost and quality; lubrication and wet grip; provision of gloves and glove sizes; other types of gloves (e.g. indicators, obstetric gauntlets); gender differences; powdered gloves; and using gloves as a tourniquet.

4.5. Conclusions

A broad range of tasks were performed with examination gloves, using many different grasp types. Although all participants currently used nitrile examination gloves, many expressed a preference for latex, with the main reason being a perception that they fitted or conformed better. Similarly, fit and elasticity were identified as key issues with nitrile gloves, and were often linked. Loss of tactility was also identified as a common issue.

Surgical gloves were used less regularly, generally for more dextrous and more specialised tasks. Most used latex gloves, although specific glove type and configuration varied depending on application. Non-latex gloves were generally used only in cases of known allergy. There was overall satisfaction with the available latex surgical gloves, although those that used non-latex alternatives had some issues, mainly that they did not “feel right”.

In those tasks perceived to be most adversely affected by gloves, the main performance requirements were fine dexterity and tactility. The two were also linked in terms of tactile feedback when manipulating tools.

The main issues with gloves identified by participants were tactile sensation, fit, comfort and donning. Reduction in tactile sensation was often linked to fit, and was identified as a reason why gloves were not worn for some tasks such as cannulating.

Hand fatigue was not identified as a major issue, and many thought that gloves were irrelevant, with stress, technique and physical exertion being mentioned as more significant factors. Some thought that tight gloves might increase fatigue.

Tearing was not a major issue, except for the orthopaedic surgeons (hence their double-gloving), and the main cause was donning, particularly on damp hands. In this case, there was no increased infection risk, since torn gloves could be changed before commencing work.

Most practitioners had opinions and preferences with regard to glove material (generally preferring latex to the alternatives), but opinion was divided on whether performance was actually affected or whether practitioners adapted to the gloves. Those that did identify performance differences commonly named inelasticity (causing poor fit and thus reducing safety) and poor tear resistance (causing time loss in replacing gloves) as the main performance issues, Participants identified a clear link between thickness and perceived *cutaneous sensibility*, but many recognised that sensitivity needed to be balanced with tear resistance, the balance depending upon the task. However, the effect of thickness on performance was much less clearly defined.

Grip pattern was not generally perceived to have an effect on performance. Fit, however, was seen as contributing to a number of issues, with loose gloves causing loss of sensation, reducing grip or obstructing, while tight gloves increased discomfort and fatigue and restricted movement. The limited sizes and shapes of the gloves were often a problem, particularly for those with short fingers, who ended up with either baggy fingertips or tight palms. This was a particular problem with the nitrile examination gloves.

Most of the participants used a double layer of gloves for high-risk surgery, and many found this to reduce tactile sensation, though most said they could still perform the tasks they needed to.

From the results of the study, a number of key areas for further research were identified: defining performance in medical practice and understanding how gloves affect it; separating and comparing the perceived effects from the measurable ones; understanding the effect of glove material (particularly elasticity and grip) on performance, and the differences between latex and non-latex (particularly nitrile) examination gloves; the effect of glove fit on both tactility and dexterity; and the effect of glove thickness on tactility. In Chapter 5, these areas are developed into a structure for the research, and used to select a number of tests for development, through which each of the areas can be explored and the performance of medical gloves more clearly understood.

5. Direction of the Research

Based on the responses of the medical professionals and the review of the current state of glove research and available test methods, the scope and structure of the project was defined as shown in Figure 18. The key areas of performance identified for further research were grip and friction, dexterity and tactility. The tests reviewed in Chapter 3 were therefore split into these three categories, which are dealt with in separate chapters (6-8). There is obviously some overlap in some tests, since dextrous tasks cannot be performed without tactile sensation or grip, but the main component of performance for each test was considered.

Furthermore, glove fit and the relationship between perceived and actual, measurable performance were both identified as areas of study. These were incorporated into a number of key tests by including glove, hand and perceived performance measurement in the test procedures, but will be discussed in greater detail in separate chapters (8 and 10).

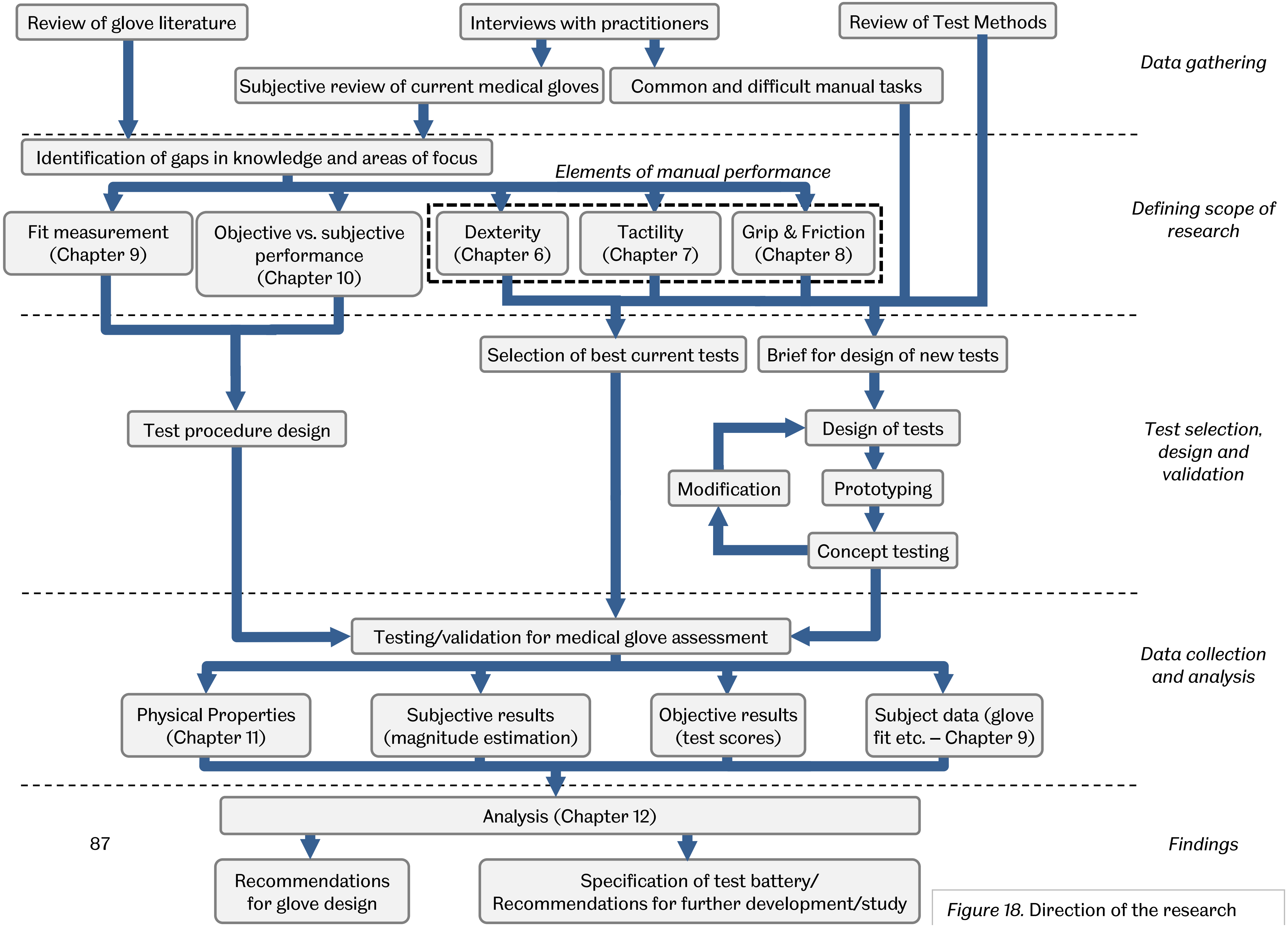

Figure 18. Direction of the research

5.1. Selection of tests to develop and validate for use with gloves

5.1.1. Selection methodology

Because of time and cost limitations, there is clearly not scope within the project to use every test method identified. Furthermore, the review has shown that some of the tests are not suitable for medical glove testing (being unable to differentiate between gloves, or even between gloved and ungloved). It is therefore necessary to focus development and testing on the most suitable tests in each of the three areas (Grip and Friction, Dexterity and Tactility). The selection process needs to take into account a number of factors:

Current discrimination/Accuracy. The ability or potential ability to discriminate between medical gloves as shown in the literature, and the accuracy of the test in defining performance.

Cost/Availability. The cost of purchasing or building test equipment, and the time and difficulty involved in acquiring or designing and making it. Some of the tests (such as the pegboards) require calibrated rigs that cannot be replicated and may only be available in other countries or not at all (as is the case with some of the older dexterity tests). Some tests require only household objects or are already available at the University of Sheffield, while others require the purchase of custom-built, large-scale test rigs with expensive measurement hardware and software.

Ease/duration of test procedure. This includes considerations such as who can perform the test. If it involves a specialised medical or dental procedure, this will limit the availability of test candidates and the length of time for which they are available in one session. It also includes the ease of setting up and operating the test equipment and processing the data. Tests that involve complex equipment and software will be more difficult to perform and take longer to analyse results, and since time is limited, this must be a consideration.

Previous validation. Those tests that have a larger bank of data available, such as the Purdue pegboard or the Semmes-Weinstein filaments, particularly with medical gloves, must get priority over newer or prototype tests, since they have more proven reliability, and results can be more easily validated with baseline ungloved tests.

Application to medical practice. Perhaps the most important factor in selecting tests is how closely they simulate medical tasks or performance elements required in those tasks. If the tests are to be useful in defining how gloves affect the performance of medical practitioners, they must, as closely as possible, replicate the skills and glove properties required in practice. In the case of grip and friction, this may be more about simulating the right friction conditions (most medical tasks involve static rather than dynamic friction) or grasp type (pinch grip, power grip etc.) whereas in the dexterity and tactility tests there will be closer correspondence between the test procedure and the task. Furthermore, in order to identify real performance differences between the gloves, the tests must replicate those tasks that are most manually challenging or in which the gloves have most effect. At this stage, this can only be determined based on the perception of practitioners, as established in the interviews (see Chapter 4).

In order to evaluate the tests with regard to the above criteria, a selection methodology is required. The Weighted Scoring Method is simple and well established (e.g. [148]). It requires each criterion to be given a weighting in terms of its importance in the selection process. The tests are then scored against each criterion (they are scored out of five in this case), and that score is multiplied by the weighting. The sum of the weighted scores for all the criteria gives the total score for the test. The scores for each test in the five categories and the weighted total are shown in Table 9, Table 10 and Table 11 (Grip and Friction, Dexterity and Tactility respectively) with the highest scoring tests at the top. The weightings chosen for each criterion are shown in brackets, e.g. *(5)*, and the tests that were selected are bordered in green. The medical task or tasks best simulated by each test are also listed where appropriate. Images of the less familiar tasks are shown below the relevant chart.

5.1.2. Test selection

Table 9. Grip and Friction Test Selection Chart

Test/Equipment	**Current discrimination/ Accuracy *(4)***	**Cost/ Availability *(4)***	**Ease/duration of test procedure *(2)***	**Previous validation *(2)***	**Application to medical practice *(5)***	**Medical task(s) simulated**	**Weighted Total**
UoS finger friction rig	4	5 (available)	4	3	1	Bending arch wire[*]	55
W&J-type pinch grip force transducer	4	2	3	4	3	Holding instruments	53
Polyco friction angle rig	4	4	3	2	2	-	52
Max. grip force tests (e.g. dynamometer)	2	5 (available)	5	3	1	-	49
B&L (or other) Pinch gauge	2	4	5	2	2	-	48
Force probe stimulation	4	2	4	1	2	-	44
Split cylinder manipulation test	3	2	2	2	3	Holding instruments	43
Rubber hemisphere friction test	4	2	3	1	2	-	42
Balanced pivot finger friction test	4	2	3	1	2	-	42
Linear trans. stage	5	1	2	2	2	-	42
Dental tool/ force plate	4	2	2	1	2	-	40
Keyboard transducer	4	2	4	1	1	-	39
Data Glove	3	1	3	2	2	-	36

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[*] Task identified by medical practitioners as being adversely affected by gloves (see Chapter 4)

Table 9. (cont.)

Test/Equipment	Current discrimination/ Accuracy *(4)*	Cost/ Availability *(4)*	Ease/duration of test procedure *(2)*	Previous validation *(2)*	Application to medical practice *(5)*	Medical task(s) simulated	Weighted Total
Tekscan pressure measurement	2	2	2	2	2	-	34
EHD tribometer	3	1	1	3	2	-	34
UMT	4	1	2	2	1	-	33

Table 10. Dexterity Test Selection Chart

Test/Equipment	**Current discrimination/ Accuracy *(4)***	**Cost/ Availability *(4)***	**Ease/duration of test procedure *(2)***	**Previous validation *(2)***	**Application to medical practice *(5)***	**Medical task(s) simulated**	**Weighted Total**
Purdue Pegboard	3	5	4	5	3	Placing crowns*, inserting grub screws*	65
Knot-tying test	2	5	3	2	5	Tying sutures*	63
Cutting out paper shapes	4	5	4	2	3	Dissecting vessels†	63
Syringe water drawing	2	5	5	2	4	Using syringe*	62
O'Connor (Finger)	4	3	4	4	3	(as Purdue)	59
Suture test	4	3	2	1	5	Suturing*	59
Bennett H-TDT	3	4	2	3	4	Removing Ilizarov frames (Figure 19)†	58

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* Task identified by medical practitioners as being adversely affected by gloves (see Chapter 4)

† Task identified by medical practitioners as particularly requiring dexterity (see Chapter 4)

Table 10. (cont.)

Test/Equipment	Current discrimination/ Accuracy *(4)*	Cost/ Availability *(4)*	Ease/duration of test procedure *(2)*	Previous validation *(2)*	Application to medical practice *(5)*	Medical task(s) simulated	Weighted Total
Dressing preparation	2	4	3	1	5	Peeling adhesive tape/dressings*, opening packets*	57
Crawford SPDT	3	3	2	4	4	Endodontic filing*, inserting grub screws*, plating fractures†,	56
Endodontic file test	3	3	4	1	4	Manipulating file rubber stop	54
O’Connor (Tweezer)	4	3	3	3	2		50
Nuts-and-bolts test	3	5	3	1	2		50
Bur block test	1	3	5	1	4	Manipulating burs	48
Enlarging canal	1	3	2	1	5	Endodontic filing*	47
Coin Rotation Task	2	4	5	1	2	Changing/ ‘palming’ instruments†	46
Minnesota RMTT	3	2	4	3	2	Turning instruments	44
Dental pin placement	1	3	2	1	4	Pin placement	42
Pennsylvania BWAT	2	3	2	3	2	Plating fractures†	40
Drawing pins and tweezers	1	4	4	1	2	Manipulating dental parts etc.	40

(continued on next page)

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* Task identified by medical practitioners as being adversely affected by gloves (see Chapter 4)

† Task identified by medical practitioners as particularly requiring manual dexterity (see Chapter 4)

Table 10. (cont.)

Test/Equipment	**Current discrimination/ Accuracy *(4)***	**Cost/ Availability *(4)***	**Ease/duration of test procedure *(2)***	**Previous validation *(2)***	**Application to medical practice *(5)***	**Medical task(s) simulated**	**Weighted Total**
Electrical socket assembly	3	4	2	1	1		39
Sollerman HFT	1	4	3	3	1		37
Cribbage board	2	3	4	1	**1**		35
Grooved Pegboard	3	1	4	1	1		31
Santa Ana Dexterity	2	2	4	1	1		31
Plug Insertion Test	1	3	4	1	1		31
Craik Screw Test	3	1	2	1	1		27
Knob/tap setting	1	2	1	1	1		21

Figure 19. Removing Ilizarov frame (stills from [149])

Table 11. Tactility Test Selection Chart

Test/Equipment	**Current discrimination/ Accuracy *(4)***	**Cost/ Availability *(4)***	**Ease/duration of test procedure *(2)***	**Previous validation *(2)***	**Application to medical practice *(5)***	**Medical task(s) simulated**	**Weighted Total**
Sponge and glue	2	4	4	1	4	Intra-uterine manipulation*, removing stitches*, per rectal examination*, feeling for lesions in bowels†	54
Roughness Discrimination Test	1	4	3	3	3	Dental filing[*], feeling tissue[†]	47
Semmes-Weinstein Monofilaments/ WEST	3	2	4	4	2		46
Haptic Identification of Common Objects	3	4	3	2	1		43
Correx dynamometer	3	2	5	1	2		42
Scaling of typodonts	1	3	2	1	4	Scaling of teeth	42
Shape/Texture Identification (STI)	2	2	3	2	3	Prosthesis positioning†, VAC dressings (Figure 20)†	41
Pipe diameter identification	2	4	4	1	1		39

(continued on next page)

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[*] Task identified by medical practitioners as being adversely affected by gloves (see Chapter 4)

[†] Task identified by medical practitioners as particularly requiring tactility (see Chapter 4)

Table 11. (cont.)

Test/Equipment	Current discrimination/ Accuracy *(4)*	Cost/ Availability *(4)*	Ease/duration of test procedure *(2)*	Previous validation *(2)*	Application to medical practice *(5)*	Medical task(s) simulated	Weighted Total
2-point discriminator test	1	5	4	1	1		39
Weight Discrimination	1	4	4	1	1		35
Knob identification	1	2	4	2	1		29
Force scaling and discrimination	2	1	2	1	2		28

Figure 20. Applying a Vacuum Assisted Closure® (VAC) dressing (reproduced from [150])

Grip and Friction. Three tests were selected for further development and testing: the **University of Sheffield finger friction rig**, **Westling and Johansson's pinch grip rig**, and the **Polyco friction angle rig**. This combination allows measurement of both static and dynamic friction. The pinch grip rig requires design, development and manufacture, but provides the best opportunity to investigate the relationship between *cutaneous sensibility* and grasping force and the effect of gloves on this.

Dexterity. Of the pegboard finger tests, the **Purdue** was chosen over the O'Connor as it was already available at the University of Sheffield and has a larger body of data available. Of the hand tool tests, the **Bennett** and the **Crawford** scored highest, and give a range of fine and gross dexterity. In terms of the applied tests, the **knot-tying** test scored highest. However, in developing this for medical simulation, it comes most commonly within the context of **suturing**, which also scored highly. It would therefore be sensible to combine the two tests. Both the paper shape cutting and the syringe tests are promising and simple tests worth exploring, but may be deferred to a later study given the limited time available. Although the paper shape cutting test and the knot-tying test were scored equally, the prominence of knot-tying and suturing in the interview responses, as well as the ability to combine the two into one test, tipped the balance in favour of the knot-tying.

Tactility. The three highest scoring tests that were selected are the **'sponge and glue'** test, which requires significant development but is the best simulation of medical examination and measures gross tactility (geometry identification); the **Roughness Discrimination Test**, which is a good test of finer tactility (texture discrimination); and the **Semmes-Weinstein Monofilaments**, which are more theoretical in their treatment of tactility, measuring the cutaneous pressure threshold.

5.2. Brief for design of new tests

5.2.1. Other medical tasks not currently simulated

A number of the tasks identified by practitioners as being adversely affected by gloves are not well-simulated by current tests, and so could provide a basis for the design of new tests:

Cannulating/finding pulse (Figure 5). Cannulating involves palpating vessels to determine the quality of the vein (does it bounce, does it drain normally) and whether it pulsates (i.e. is it a vein or an artery?), and inserting a needle into the vessel. The task involves tactility (both through the fingers and through the needle), dexterity and active haptic sensing. Official teaching (e.g. [151]) tells medical students to initially palpate the vessel before putting gloves on, but many practitioners do the whole procedure without gloves because they cannot feel the vessel or the pulse. None of the active haptic sensing tests are on a small enough scale to be relevant to this problem. Any test to assess the effect of gloves on the task would need to involve hidden pressurised vessels, preferably with the ability to pulsate the fluid. Such an apparatus has been designed for training purposes (see Figure 21), and the concept could be replicated in the lab using a simplified rig. Similar dexterity is used in inserting epidurals and an even greater degree required in cardio procedures such as inserting pacemaker wires and catheters.

Figure 21. Arterial Puncture Arm (reproduced from [152])

Laparoscopic surgery/endoscopy/arthroscopy of the knee. *Laparoscopic surgery* involves very fine movements using instruments with scissor grips. Endoscopy involves feeding a tube through the hands and twisting it to get round corners. Arthroscopy (Figure 22) is similar to endoscopy, but also involves treatment, which is somewhat similar to *laparoscopic surgery*. Manual dexterity and tactile feedback are required for all three. None of the currently available tests correspond well to these tasks, although laparoscopic training equipment is available.

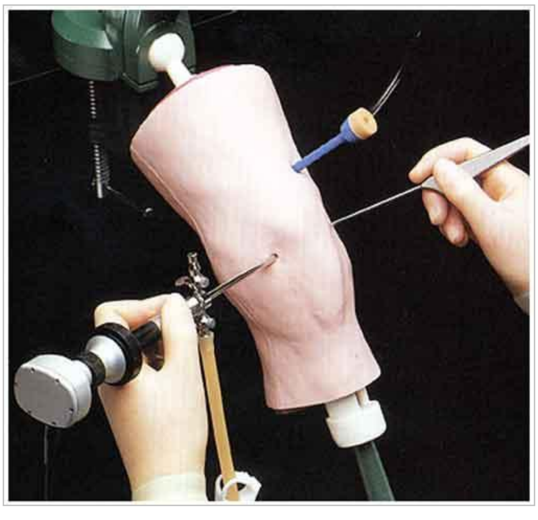


Figure 22. Knee arthroscopy (reproduced from [153])

Intubation. Intubation (Figure 23) is the insertion of a plastic catheter (usually into the trachea). It normally uses a laryngoscope (a viewing instrument with a blade, as shown) to visualise the vocal cords. Dexterity and grip are required to manipulate the mouth and the tube, and it is often done without gloves.

Figure 23. Intubation (reproduced from [154])

Further to those tasks identified as being most adversely affected by gloves, participants also identified tasks requiring the most dexterity and tactility. These may or may not be affected by the gloves, but provide a useful basis for testing since:

- they are tasks carried out regularly by medical practitioners
- they are sufficiently difficult to expect some difference in the level of performance with different gloves.

Taking elastics off dental brackets (Figure 24). This requires fine manual control of a probe to take elastic bands off a brace without piercing the gum or the lip. The only fine tool dexterity tests currently available use tweezers with pegs. A test could easily be designed using a *typodont* (e.g. Figure 25).

Figure 24. Taking elastics off a brace (still image from [155])

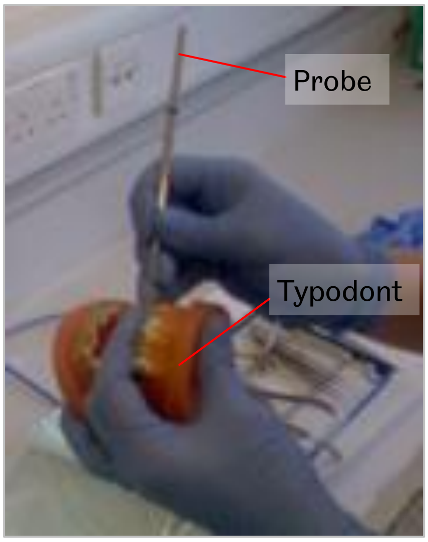


Figure 25. Removing elastics from a typodont

Surgical approach/using scalpel. Using a scalpel requires a steady hand and the application of the correct pressure. There is no test that reproduces the skill required.

Prosthesis positioning. This requires fingertip dexterity and tactility. The prosthesis (artificial body part) needs to be precisely moved into position and checked with fingertips. No tests simulate this kind of fingertip manipulation of objects. Haptic identification tests such as the STI may approximate what is required to assess the position of the prosthesis e.g. feeling edges and shape.

Bone preparation. Preparation of hip sockets etc. requires well-directed force with hammer and chisel to ensure the right bits are removed.

Using ophthalmic chopper (Figure 26). This is a very fine hook that is rolled between the thumb and forefinger and moved with wrist to manipulate the lens in the eye and chop it into pieces. The rolling movement is somewhat like the endodontic filing, so the Crawford test is relevant, but the movement is more precise. A test where an object is moved around using a thin cylindrical tool could easily be designed.

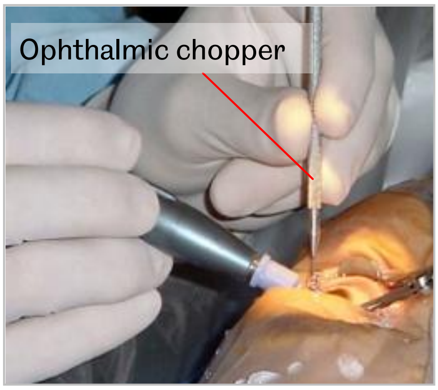


Figure 26. Cataract surgery using ophthalmic chopper (reproduced from [156])

Manipulating bowel. Separating loops etc. The issue is handling slippery tissue. The use of fat in dexterity tests could simulate some of the problems encountered, but no current tests simulate handling soft tissue.

Using dental handpiece. Dentists use a pen grip with a handpiece to perform fine movements such as removing decayed material. Tactile feedback is required to remove the correct material (see Figure 27).

Figure 27. Dental handpiece (reproduced from [157])

Fracture fixation. This involves feeling bony landmarks and fracture fragments through swelling. The sponge and glue test is less appropriate for this, as the bumps are under soft tissue. A new test is needed to properly simulate this kind of tactility.

Removing trapezium bone. The tasks requiring tactility are: feeling through the scalpel to stay on edge of the bone, feeling for remaining bone fragments, and palpating the forearm tendon (which is removed to form a pad to fill the area left by the trapezium bone). No tests particularly apply.

Feeling soft tissue tension. Knot tying rigs exist that use magnetic weights to simulate tissue tension, but they are not specifically designed for feeling it.

Pressure on power tool. When using power tools such as drills, saws and reamers, it is necessary to feel how much force or torque is being applied so as to control the amount of material removed. None of the current tactility tests are relevant to this type of sensation.

Injecting anaesthetic into the eye. It is necessary to feel the resistance of the eye so as to push the needle in the correct distance and not damage the eye. There are no relevant tests for this kind of tactility.

5.2.2. Proposed new tests

Many of the tasks identified involve handling tools and instruments that vary in size and shape from power tools or endoscopes to scalpels, ophthalmic choppers and dental probes. In order to measure realistic grip forces on the instruments and to allow repeatable friction tests that are independent of the test subject, whose hand dimensions, fatigue levels and skin moisture content among other things will affect results, it was proposed that an anthropomorphic device (an artificial hand) be created. This would need to be flexible so that it can be posed into different grasps and a force applied to the fingertips. The development of the device is detailed in Chapter 8.

As well as feeling for surface irregularities in tissue such as lesions or scar tissue, some of the tasks identified required the identification of stiffness changes under the surface, such as locating bone fragments in orthopaedic surgery. It was therefore proposed that along with the modification to the 'sponge and glue' test, a further test involving the location of hard lumps in simulated soft tissue be developed. The development of both tests is detailed in Section 7.4.

The tasks most commonly identified as being difficult with gloves were cannulating and feeling a pulse, with the tactile elements of location and palpation of blood vessels being the main problems. It was therefore proposed that a test be developed based around the location of a pulse in a simulated blood vessel. The development of the test is detailed in Section 7.7.

Equipment was also available at the University of Sheffield that had been used to simulate a dental examination and measure the applied force on the teeth [158].

Since the dental tests reviewed were mostly impractical for this study, and since a number of the tasks identified used precision dental equipment, it was decided to modify the test rig to produce a test that could compare the effect of glove type on the tactile ability and force applied by dentists in an examination.

5.3. Novelty of work

The need for further study of medical glove performance and the glove properties that affect it, and hence for a battery of tests that are repeatable, quantifiable and realistic, by which new and existing gloves can be assessed, has already been discussed in Chapter 2. While some tests have been carried out using medical gloves, and some have attempted to define batteries of tests for gloves, no attempts have been made to identify the medical tasks in which gloves cause the most difficulty for practitioners, and to use the results in the selection of appropriate tests.

Furthermore, efforts to produce new medical-based tests have so far been limited to simple equipment such as syringes and water or sponges and glue. The tests detailed here have required significant development, often going through several rounds of design, prototyping, testing and re-design in an attempt to produce a realistic simulation that adequately quantifies differences in glove performance. The work also aims to go further than previous work in identifying and characterising the factors that contribute to medical glove performance.

6. Dexterity

6.1. Introduction

In Chapter 5, three standard dexterity tests – the Purdue Pegboard Test, the Crawford Small Parts Dexterity Test and the Bennett Hand-Tool Dexterity Test – were chosen for further validation with medical gloves. The aim was to determine how well they were able to differentiate between different gloves in terms of their effect on the performance of medical tasks. The dexterity involved varies from fine, finger dexterity to fine tool dexterity (tweezers and screwdrivers) and coarse dexterity (spanners). Further to these established tests, a test was to be developed around suturing and knot-tying, building on the work done by Gnaneswaran et al. [53] and Bishu et al. [102].

6.2. Methods

The standard dexterity tests require no previous experience or specialised skills and so can be performed by anyone with a degree of manual dexterity. Suturing, however, is a specialised skill and required qualified doctors who had some experience of suturing. In order to make the most efficient use of available subjects, some of the tests were combined into small batteries, including both dexterity and tactility tests, so that they could be carried out consecutively within one session.

6.2.1. Ethical approval

All the tests protocols for the project, along with participant information sheets and consent forms, were submitted to the University of Sheffield Research Ethics Committee (REC) and received approval. For the tests involving NHS staff, the research was included as an extension to the previous study (Chapter 4). Following a change in NHS policy, it was sufficient for evidence of approval from the University REC to be provided to the local NHS REC. Relevant documentation is provided in Appendix B.

6.2.2. Test Battery 1

The first set of tests consisted of the Purdue Pegboard Test (Section 6.3), the Crawford Small Parts Dexterity Test (Section 6.4) and the Semmes-Weinstein Monofilaments (detailed in Chapter 7).

Subjects. 18 volunteers took part in the tests. They were all students at the University of Sheffield between 21 and 30 years of age. 16 of the subjects were male and two were female. They were required to be generally healthy and have no known sensorimotor deficiencies.

Gloves. The gloves used were POLYCOHealthcare ambidextrous examination gloves that were donated by BM Polyco Ltd as part of the project. Three types were used in this study (see Figure 28):

- Finex® PF (powder-free) latex gloves, which are chlorinated on the outside surface to reduce allergens and coated with a polymer on the inside to improve donning
- Finite P Indigo AF (*accelerator*-free) nitrile powder-free gloves, which has textured fingertips
- Finity PF (powder-free) vinyl gloves

The properties of the gloves, including thickness, elasticity and tear strength, are given in Chapter 11.

Figure 28. Examination gloves used in testing (a) latex, (b) nitrile and (c) vinyl (reproduced from [159])

Each of the three gloves had five available sizes: Extra-Small (XS), Small (S), Medium (M), Large (L) and Extra-Large (XL). For this battery of tests, it was decided to use the latex and vinyl gloves (due to limited nitrile supplies at the time).

Variables. The independent variable, or 'within-subjects factor', in all the tests was hand condition, consisting of five levels: 'No Gloves', 'Best-Fit Latex', 'Best-Fit Vinyl', 'Double Best-Fit Latex' and 'Larger Latex'. These conditions allowed for analysis of the overall effect of wearing gloves, of glove type and fit, and of double-gloving.

Glove selection. The subjects were allowed to choose the size of glove that fitted them best, with some advice from the researcher (since most had little or no experience of wearing examination gloves). The latex and vinyl gloves were comparable in dimensions for each of the five sizes, so there was no variation in best-fit glove size between the two types. The 'Larger Latex' gloves were chosen at two sizes larger than the best fit, except for the four candidates that chose the 'Large' size gloves as 'Best Fit', who were assigned 'Extra-Large' as their larger size. For the 'Double Best-Fit Latex', subjects wore two layers of best-fit latex gloves.

Location. The tests were performed in a laboratory at the University of Sheffield. Subjects were seated at a standard height table on which the test rigs were placed.

Experimental design. It was decided to perform the tests in six different sessions on separate days, with each glove type worn for one session, and the 'No Gloves' condition for the first and last sessions. The main reasons for carrying out the tests in separate sessions were: to avoid hand fatigue, to reduce the effect of learning, and to increase the availability of test subjects (each session took around 15-20 minutes, and most participants were more willing to give time in short sessions than for one session of 1.5-2 hours). It was recognised that participants' energy levels, skin moisture or other factors might vary from day to day, but it was decided that the benefits, particularly of reducing hand fatigue, outweighed the costs. Furthermore, the order of the four gloved conditions was randomised to reduce or eliminate some of these factors. It was decided to perform the first and last sets of tests with no gloves in order to provide a baseline measure, independent of learning or glove type, to which the individual gloved tests could be compared. (For the Semmes-Weinstein Monofilaments, only one 'No Gloves' test was performed, since learning behaviour is not a factor.) This also allowed for some learning to be done before the gloved conditions were tested, these being the most important for comparison. Ideally, the subjects would have performed the test multiple times before recording the results, but the available time did not allow for this. The order of the two dexterity tests was randomised to allow a fair comparison between the tests in terms of their discrimination, so that one test was not more affected by hand fatigue than the other.

Fit measurement. After the tests were completed, the subjects' dominant hand size was recorded by placing it on a sheet of graph paper and photographing it. The fit measurement process is described further in Chapter 8.

6.2.3. Test Battery 2

The second set of tests consisted of the suturing test (Section 6.6) and the Pulse Location Test (detailed in Chapter 7). These tests were grouped together because of the level of medical expertise required by the subjects.

Subjects. 19 volunteers took part in the tests. They were recruited from Sheffield Teaching Hospitals (STH) staff. Subjects were required to be generally healthy and have no known sensorimotor deficiencies and a basic ability to suture. This meant that all the subjects were practising doctors, ranging from House Officers with less than two years' experience to Consultants with more than twenty. Ten subjects were male and nine were female. All subjects were currently using nitrile examination gloves, and some had previously used latex ones.

Gloves. As with Test Battery 1, the gloves used were POLYCOHealthcare ambidextrous examination gloves. However, for this set of tests, Finex PF latex and Finite P Indigo AF nitrile were used. Nitrile gloves were included rather than vinyl since they are much more widely used in hospitals, and the examination gloves currently used throughout STH are nitrile. The comparison with latex (which was previously the standard for medical practitioners) is therefore more interesting.

Variables. The within-subjects factor in both tests was hand condition, consisting of three levels: 'No Gloves', 'Best-Fit Latex' and 'Best-Fit Nitrile'.

Glove selection. The subjects were allowed to choose the size of glove that fitted them best, usually the size they used on a regular basis. One subject used a larger size for the nitrile gloves as they found their usual size too tight, but the rest used the same size for both glove types.

Experimental design. The limiting factor in the design of the test session was the time available with doctors. Initial consultation with the STH local contact (a general surgeon) suggested that the maximum time we could expect staff to give during work time (when recruitment would be easiest) would be 15-20 minutes. There was therefore no time to repeat the 'No Gloves' condition or to allow some opportunity to practise before recording the results. The order of the three hand conditions was therefore randomised to reduce the effects of learning on the overall mean scores.

Location. To increase the availability of medical practitioners, the tests were performed at STH hospitals (apart from one participant who was tested at the University of Sheffield) in a location that was practical for the participant – usually a coffee room or office.

Perception testing. At the end of all tests, participants were asked to score each test on a scale of their choice representing how well they felt they performed with each hand condition. The process is described further in Chapter 10.

Fit measurement. After the tests were completed, the subjects' dominant hand size was recorded by placing it on a sheet of graph paper and photographing it. The fit measurement process is described further in Chapter 8.

6.2.4.Statistical analysis

Performance will clearly vary between subjects, so that the error in mean scores for each hand condition could be fairly large in comparison to the variation between hand conditions. However, since it is the differences between hand conditions that are of interest, significance testing must be in the form of paired difference tests such as repeated-measures analysis of variance (ANOVA) and paired-samples t-tests.

These take the difference in the value of the dependent variable (e.g., time, score) between two “levels” of the factor (e.g., hand condition) for each subject (for example, the difference in completion time between tests using latex and nitrile gloves) and compare the mean difference across the subjects with the error to find the significance of any difference in the means.

Unless otherwise stated, the significance level used is 5% ($\alpha = 0.05$), and the null hypothesis is that the difference between paired responses (i.e. two tests performed by the same subject with different hand conditions) has a mean value of zero. If the probability, p, of the mean difference being zero, is less than α (0.05), the null hypothesis is rejected and the mean responses for the two hand conditions are said to be significantly different. In the case of repeated-measures ANOVA, the null hypothesis is that the mean response for all levels is equal, and the alternative hypothesis, if p is less than α, is that at least one level has a significantly different mean response.

The repeated-measures ANOVA requires that there are no missing values. Therefore, any subjects who did not manage to complete the tests with all hand conditions were only included in the paired t-test analysis.

Each data set was tested for normality with the Shapiro-Wilk test, which is most appropriate for small data sets. For those tests in which the null hypothesis of normality was clearly rejected, non-parametric equivalents were used (the Friedman Test for multiple related samples and the Wilcoxon Signed Ranks Test for paired significance testing). These compare the mean ranks of the samples rather than mean scores. While this means that the assumption of normal distribution of the population is not necessary, the significance of the results may be less apparent. A description of the statistical tests used can be found in Appendix C.

In order to compare the different tests fairly in terms of their ability to measure the performance differences between gloves, the mean difference in performance of each gloved condition to the ‘No Gloves’ condition was calculated as a percentage of the mean ‘No Gloves’ performance i.e. for n subjects:

$$\frac{\sum_{i=1}^{n}(Gloved\ score_i - 'No\ Gloves' score_i)}{\sum_{i=1}^{n} 'No\ Gloves' score_i} \times 100$$

The relative performance is shown as a bar chart for each test (e.g. Figure 31). Some tests were scored in terms of completion time, meaning that in order to compare ‘performance’ in a similar way to others that had a score for number of completions of a task, the inverse of completion time was calculated. The 95% confidence intervals in the mean percentage difference are also indicated.

For those tests where learning behaviour was expected and the ‘No Gloves’ condition was tested twice, the ‘No Gloves’ score was generally calculated as an average of the initial and final scores. In order to compare fairly with the gloved conditions, a linear relationship between test session number and score must be assumed. In order to test this assumption, the mean scores for each session were plotted, and for the first battery, one candidate was chosen to repeat the test a number of times in the ungloved condition. For those tests where it was considered that the assumption of linearity was not valid, the ‘No Gloves’ score was adjusted based on the learning curve found.

6.3. Purdue Pegboard Test

6.3.1. Apparatus and test procedure

The Purdue Pegboard and its administration have been described in detail elsewhere (e.g. [124]). The apparatus can be seen in Figure A 20. It consists of a board with two columns of holes and four ‘cups’. The left- and right-most cups contain metal pins, while the central two contain collars and washers. The procedure comprises four tests: Left Hand Test, Right Hand Test, Both Hands Test and Assembly.

In the first three tests, the subject is given 30 seconds to place as many pins as possible, one at a time, into the holes, with the right hand, left hand and both simultaneously, starting at the furthest hole or pair of holes and moving down the column(s). A combined score is obtained from the sum of the scores for the three tests (with the ‘Both Hands’ score being the number of pairs placed). In the Assembly test, the subject builds an ‘assembly’ in each hole using both hands alternately, starting with a pin, then placing a washer, a collar and another washer onto the upright pin. The subject is given one minute to complete as many assemblies as possible. The score is obtained from the total number of parts assembled (1 assembly = 4 parts). Since dropping instruments or materials can be very important to performance (for example in dental surgery where a rubber ‘dam’ is placed in the patient’s mouth to prevent dropped parts going down the throat), it was decided to record any dropped parts. Subjects were instructed to pick a new part from the cup if they dropped one, rather than attempting to pick it up, so as not to add a further time penalty. For details of the experimental design, see Section 6.2.2.

6.3.2. Purdue Combined Results

Learning behaviour. As discussed in Section 6.2.4, it was important to establish the learning behaviour of subjects in order to determine the fairest way to compare the ungloved and gloved results. This was done in two ways: by taking the mean score for each test session, and by having one naive subject perform the test repeatedly in the ungloved condition. The results are shown in Figure 29.

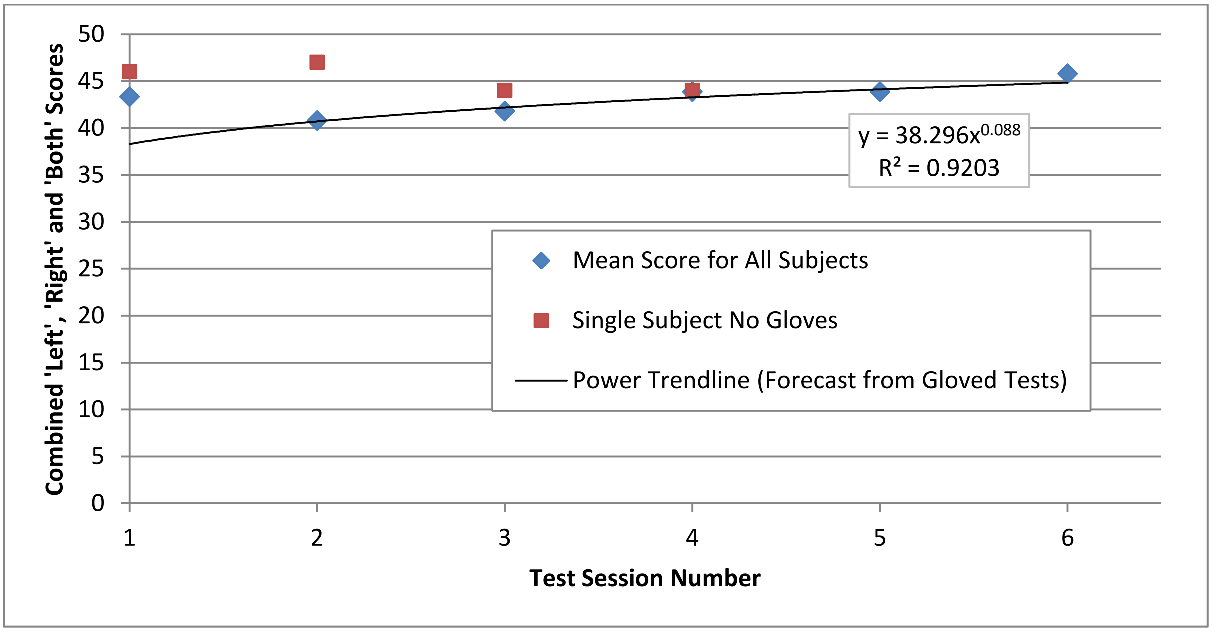


Figure 29. Learning behaviour for the Purdue Pegboard (Combined)

Learning behaviour is expected to be non-linear, being steepest at the beginning and levelling off after some time so that no further learning occurs. The gloved results fit a power trend with a correlation of 0.92, varying slightly from linearity, and the projected average of tests 1 and 6 is less than the projected average of tests 2-5. However, the single subject tests show a much flatter learning curve, and the mean score for the first test is much higher above the curve than for the last test, suggesting that the learning curve is not as steep for the first test as predicted. The assumption of linearity is therefore as good an approximation as any and requires less manipulation of the data.

Results. The results of the combined Left Hand Test, Right Hand Test and Both Hands Test are shown in Figure 30. It can be seen that the best score was achieved in the ungloved condition, while the worst score was achieved with the larger gloves. The vinyl scored slightly higher than the latex. The most pins were dropped when wearing a double layer of latex gloves (0.91 per test), and the least with the larger latex gloves (0.55 per test).

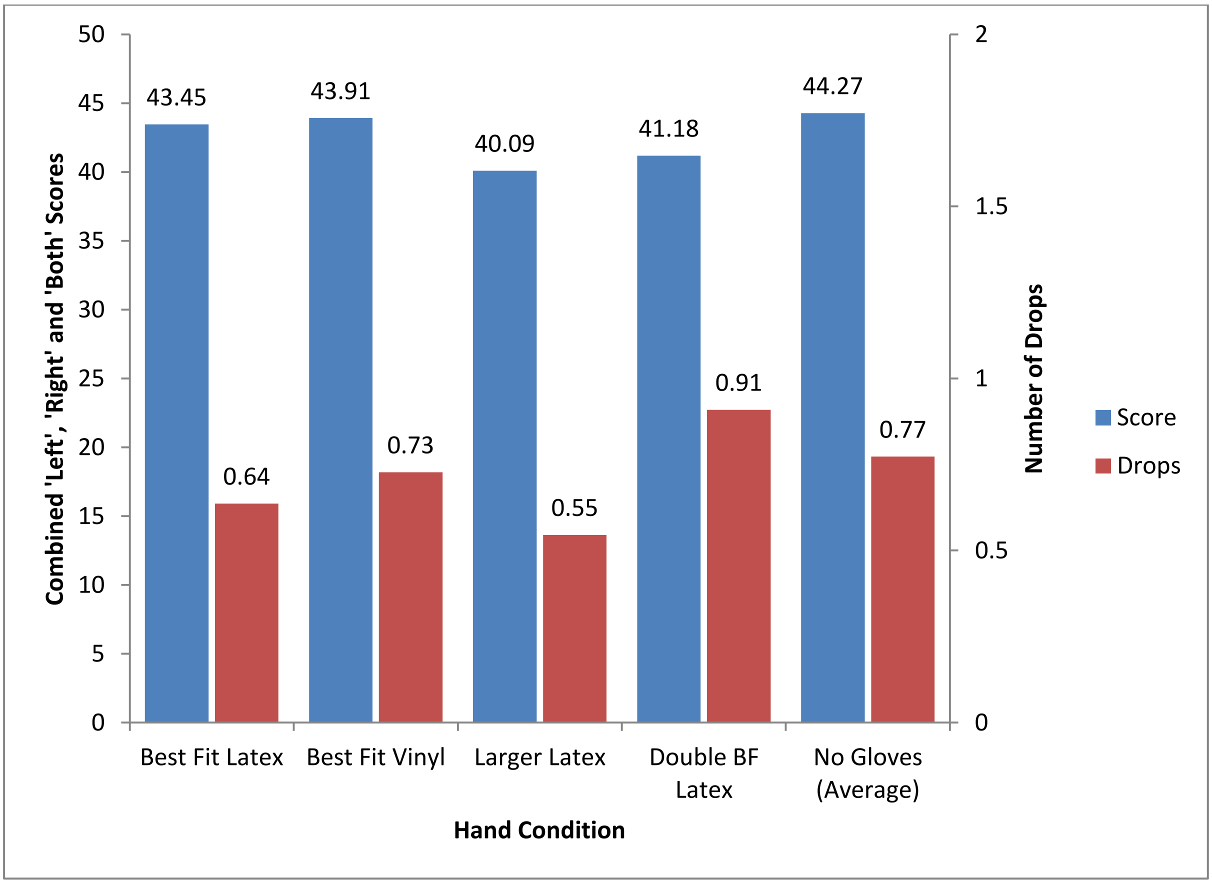


Figure 30. Mean combined scores and number of drops from the 'Left Hand', 'Right Hand' and 'Both Hands' Purdue Pegboard Tests

Figure 31 shows the relative performance of the four gloved conditions to the ungloved condition (using only the combined score, and taking the average of the two 'No Gloves' tests again). The 95% confidence levels are shown for an indication of significance.

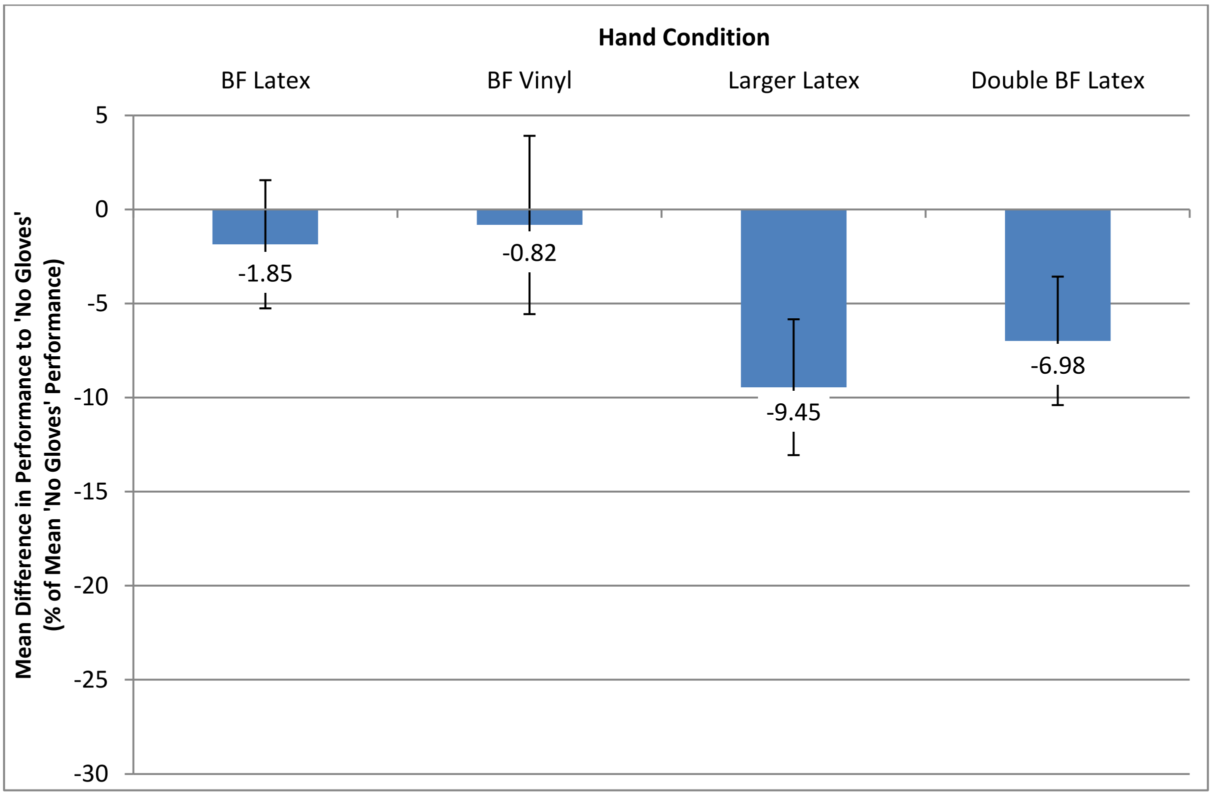


Figure 31. Comparison of Purdue combined (Right + Left + Both Hands) scores for different hand conditions with average 'No Gloves' score (shown as the mean difference to the 'No Gloves' score as a percentage of the mean 'No Gloves' score, with values shown below columns and 95% confidence intervals indicated)

The Shapiro-Wilk test showed no significant deviation from normality for any hand conditions ($p \geq 0.264$), so repeated-measures ANOVA was used. Hand condition was found to have a significant effect on performance ($p = 0.002$). The results of paired t-tests between each of the hand conditions are shown in Table 12 (where 'NS' indicates no significant difference and 'S' indicates a significant difference between the two conditions). It was found that the results split into two groups that were significantly different from each other. The two single-layer, best-fit glove conditions and the ungloved condition were not significantly different from one another, but the larger latex gloves and the double layer of gloves produced a significantly worse performance in the combined test. Figure 32 is a schematic of the differences between the variables. Those that performed best are to the left of the diagram, with the worst being on the right. Variables that overlap in the horizontal axis are not significantly different from each other, while those between which a horizontal gap exists differ significantly in their performance. The diagrams are entirely schematic, and the size and spacing of the boxes are not exactly proportional to any statistical values.

Table 12. Paired t-test for Purdue (Combined) results

	Best Fit Latex	Best Fit Vinyl	Double BF Latex	Larger Latex
No Gloves	NS (0.404)	NS (0.772)	S (0.001)	S (0.000)
Best Fit Latex		NS (0.951)	S (0.010)	S (0.018)
Best Fit Vinyl			S (0.034)	S (0.031)
Double BF Latex				NS (0.802)

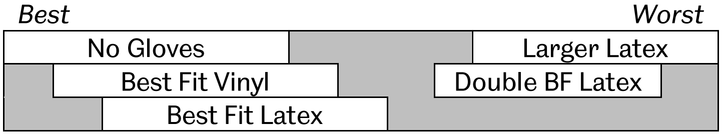


Figure 32. Schematic of significance for Purdue (Combined) results

When the score was adjusted to include the combined number of drops for the three tests by subtracting them from the combined scores, the only differences were that the ‘Double Best-Fit Latex’ scored less than the ‘Larger Latex’, and the probability of the means of the ‘Larger’ and the ‘Best-Fit’ latex being equal increased to just above the significance level ($p = 0.052$, see Figure 33).

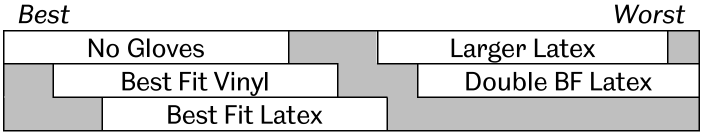


Figure 33. Schematic of significance for Purdue (Combined) results including drops

6.3.3.Assembly Results

Learning behaviour. As with the combined results, the assembly test shows a slight non-linearity (Figure 34), as expected, but the single subject tests do not show a steep learning curve, which is a somewhat unexpected result. Larger-sample testing of learning behaviour would give a clearer picture. However, based on the available data, the assumption of linearity is a reasonable one.

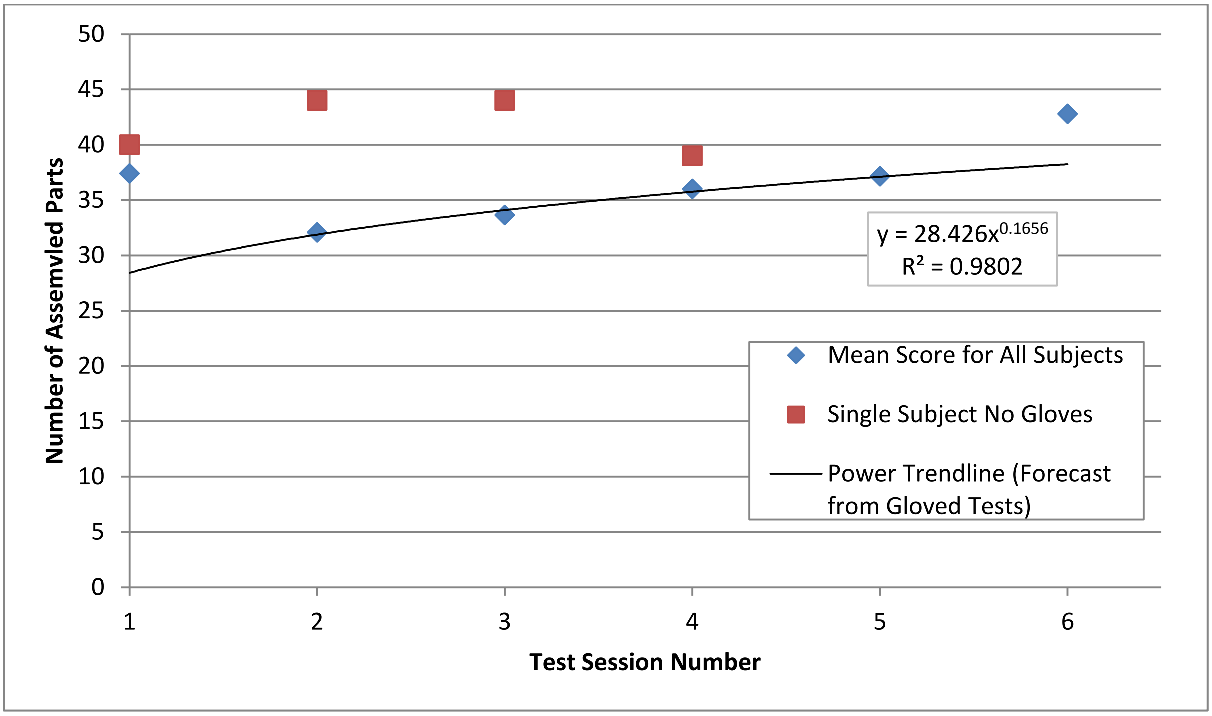


Figure 34. Learning Behaviour for the Purdue Assembly Test

Results. The results of the Assembly test are shown in Figure 35. The highest score was achieved in the ungloved condition again, while the lowest score was again achieved with the larger gloves. In contrast to the combined tests, the 'Best-Fit Latex' scored higher than the 'Best-Fit Vinyl'. As with the combined tests, the most drops occurred when wearing a double layer of latex gloves, but the least occurred with the vinyl gloves.

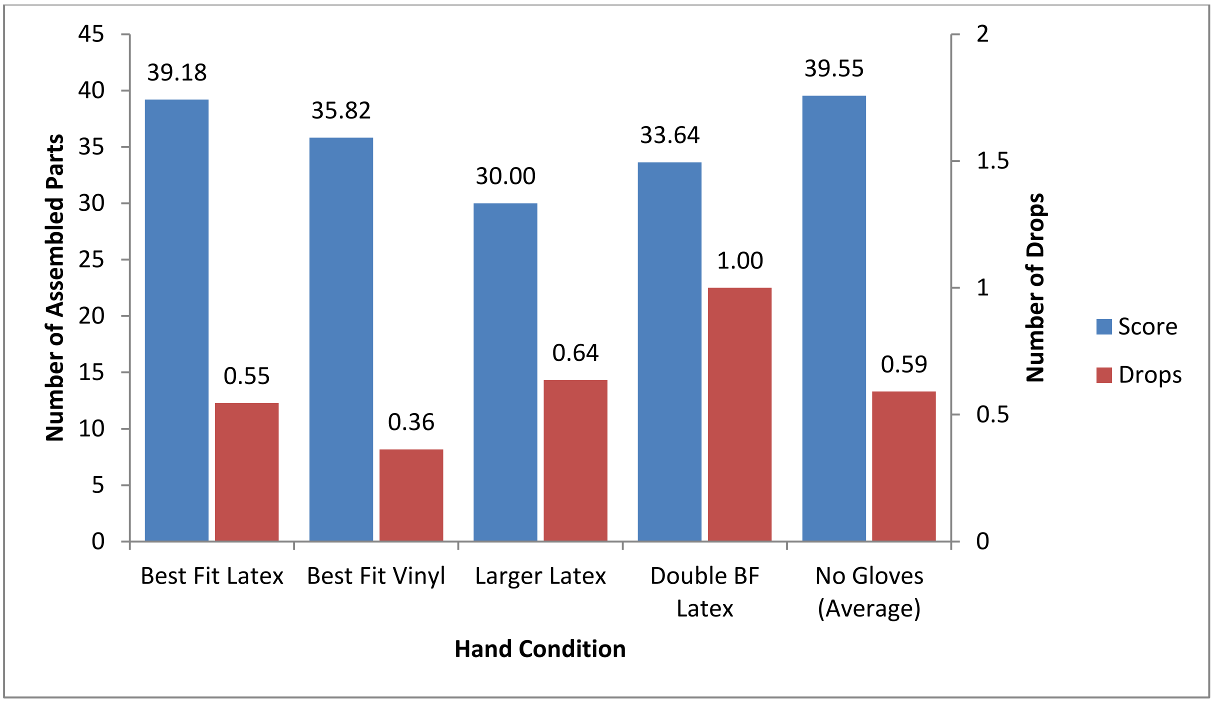


Figure 35. Mean number of assembled parts and number of drops for the Purdue Assembly test

Figure 36 shows the relative performance (number of assembled parts) of the four gloved conditions to the ungloved condition, along with 95% confidence levels.

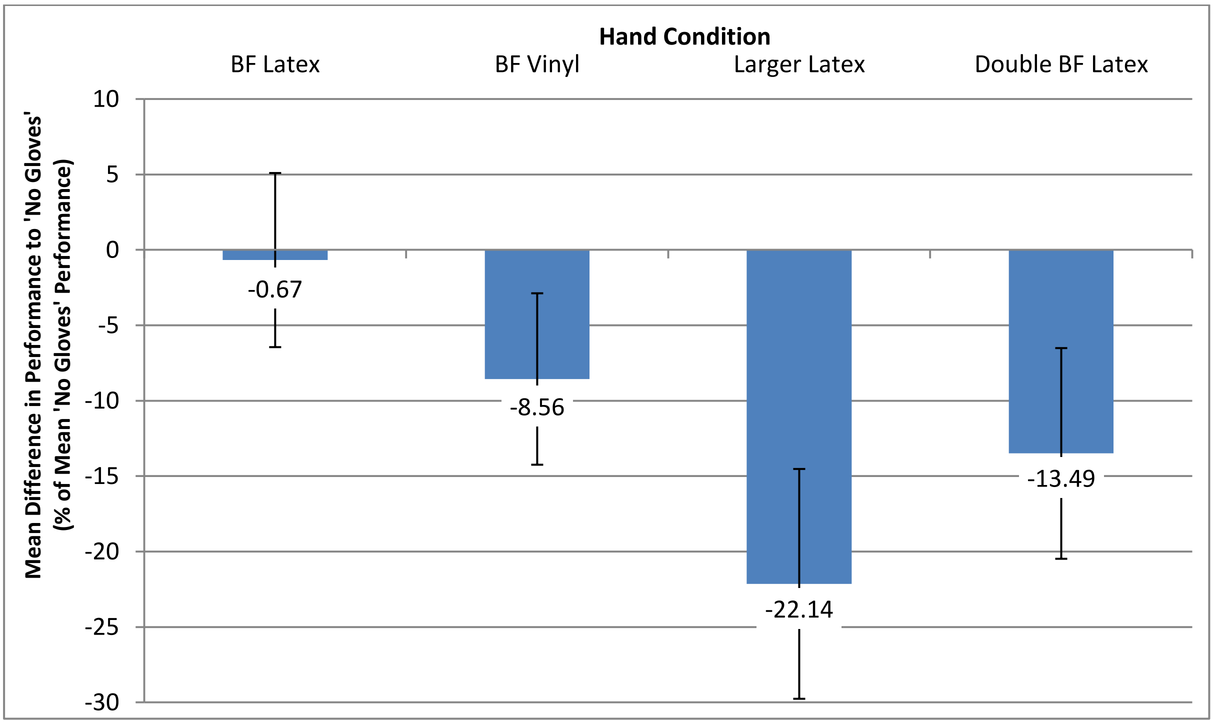


Figure 36. Comparison of Purdue Assembly scores for different hand conditions with averaged bare-handed score (with 95% confidence intervals)

The Shapiro-Wilk test showed no significant deviation from normality for four of the five hand conditions, so repeated-measures ANOVA was used. Hand condition was found to have a significant effect on performance (p = 0.000). Paired t-tests between each of the hand conditions (Table 13) found that the mean performance for the 'No Gloves' and 'Best-Fit Latex' were significantly higher than for the 'Larger Latex' and 'Double Best-Fit Latex', but the performance with vinyl gloves was not significantly different from any of the other conditions. Figure 37 is a schematic of the significance of differences between the variables.

Table 13. Paired t-test for Purdue Assembly results

	Best Fit Latex	Best Fit Vinyl	Double BF Latex	Larger Latex
No Gloves	NS (0.674)	NS (0.115)	S (0.000)	S (0.000)
Best Fit Latex		NS (0.256)	S (0.004)	S (0.012)
Best Fit Vinyl			NS (0.115)	NS (0.068)
Double BF Latex				NS (0.358)

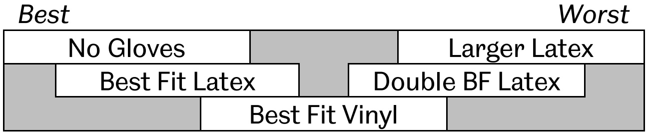


Figure 37. Schematic of significance for Purdue Assembly results

When the score was adjusted to include the number of drops by subtracting them from the number of assembled parts for each test, the only difference was that the 'Double Best-Fit Latex' scored the worst and was significantly less than the 'Best-Fit Vinyl' in the paired t-test (p = 0.050).

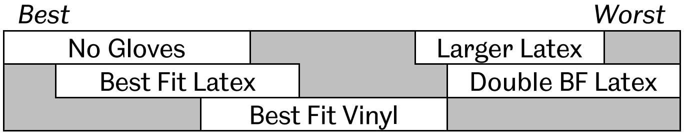


Figure 38. Schematic of significance for Purdue Assembly results (including drops)

6.3.4. Discussion

Both the Purdue Combined (Left + Right + Both) and the Purdue Assembly tests showed similar trends in score, with the highest score being achieved with ungloved hands, followed by the two best-fit single-layer examination gloves, the double layer of best-fit latex gloves, and the larger latex gloves performing worst. Some subjects commented that the loose material of the larger gloves tended to catch, particularly on the smaller parts of the assembly, but also in the holes, making it difficult to release the pins, which could account for the performance reduction.

Wearing a double layer of gloves also significantly reduced performance compared to a single layer of the same gloves in both tests, and also produced by far the most drops in both tests. A possible reason for this increase in drops is the reduction in *cutaneous sensibility* caused by the extra layers. The extra thickness reduces the ability of tactile cues to be felt, and the movement of the two layers against each other could be distorting the signals further. This tactile feedback allows the subject to detect when parts are slipping and increase the grasping force (see Section 8.3), so a reduction in *cutaneous sensibility* could increase the frequency of drops.

Neither of the tests was able to find any significant difference between the two glove types (latex and vinyl) or between the ungloved and single-layer best-fit gloved conditions, although the difference was more pronounced in the assembly test. The resolution of the tests is fairly coarse. In both tests, the difference between the means of the 'No Gloves' and the 'Best Fit Latex' conditions was less than the resolution of the test (one pin, pair of pins or assembled part). A subject who successfully places one more pin could increase their score by two to three per cent compared to one who does not quite place the pin or part in time.

The significance of the differences could be increased by using a larger sample size, but this is not very practical for the amount of testing required in glove development. The resolution could be improved by increasing the test time, but this starts to introduce an element of fatigue (which was already noted as an issue for some of the participants), as well as making larger-scale testing even more difficult.

The Purdue test was originally designed to test the ability of the participants: their hand-eye co-ordination, bi-manual dexterity and brain function (such as moving both hands in order on the assembly task). These aspects are not relevant to glove design. The difference between left- and right-handed performance is also irrelevant. The Combined test is therefore not thought to show anything useful that the assembly test does not show. The test time could therefore be significantly reduced, allowing for a larger population to be tested. More pure dexterity tests, where less brain activity occurs, might find greater differences between gloves.

6.4. Crawford Small Parts Dexterity Test

6.4.1. Apparatus and procedure

The Crawford Small Parts Dexterity Test (described in [130] and shown in Figure A 27) consists of two parts. In the ‘Pins and Collars’ test, subjects use tweezers to place pins in a holed board and then place flanged collars over them (before moving on to the next pin). The test score is the time taken to complete 36 pin-collar assemblies in six rows. A practice row of six holes is provided. As with the Purdue tests, the number of dropped parts was also recorded, although this is not part of the standard scoring.

In the ‘Screws’ test, subjects pick up custom screws by hand and screw them into threaded holes until the threads have just engaged. A flat head screwdriver is then used to screw them down until the threads disengage and they drop onto the tray beneath. As with the ‘Pins and Collars’ test, the test score is the time taken to screw in 36 screws in six rows, and a practice row of six holes is provided.

Preliminary testing showed that the ‘Screws’ test was taking well over ten minutes to complete and was causing serious hand fatigue. This was much longer than would have been expected given the data provided with the test. Discussions with the supplier did not resolve the discrepancy, and so it was decided to shorten the test by asking the subjects to complete only two rows (12 screws). For details of the experimental design, see Section 6.2.2.

6.4.2.‘Pins and Collars’ Results

Learning behaviour. Figure 39 shows the learning behaviour for the ‘Pins and Collars’ test, including the mean result across all subjects (tests 1 and 6 being ‘No Gloves’ and tests 2-5 being gloved) and the results for the one subject who completed four ungloved tests.

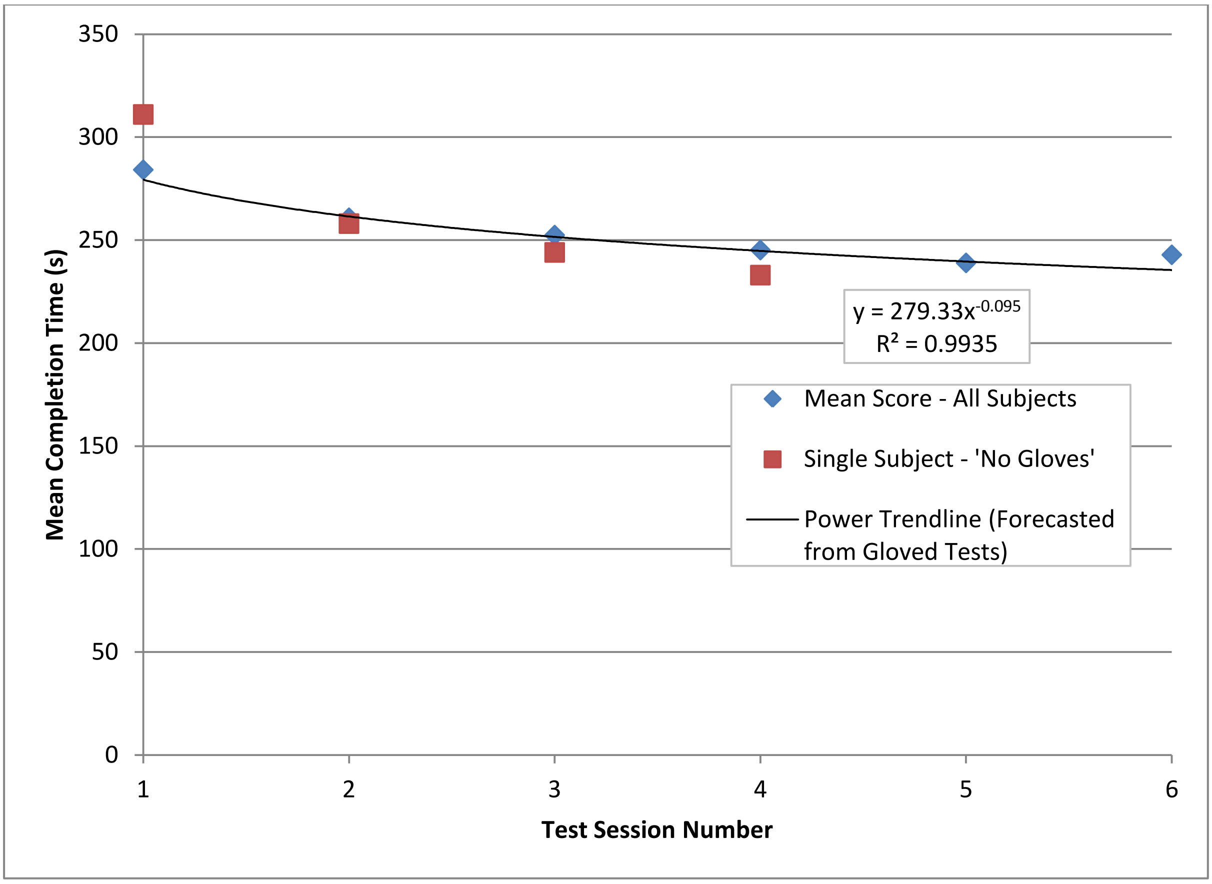


Figure 39. Learning Behaviour for Crawford 'Pins and Collars' Test

The single-subject tests suggest a steep learning curve, and therefore taking the average of the first and last session scores may not be a fair comparison. Given the nature of a learning curve and its tendency to flatten out as learning increases, taking the final 'No Gloves' score may be a more reliable indicator. Using the power curve equation, the final 'No Gloves' score was corrected (an increase of 6% in mean time taken) to make it comparable with the gloved tests (the order of which were randomised between tests 2-5). This still made it 3.4% lower than taking the average of the two 'No Gloves' tests.

Results. The results are shown in Figure 40. The lowest mean completion time was achieved in the 'Best-Fit Latex' and 'Best-Fit Vinyl' conditions. The worst performance across the test group as a whole was with the double layer of latex gloves. Figure 41 shows the relative performance of the gloved conditions to the ungloved condition, performance being defined as the inverse of completion time. Only when 'double-gloving' did subjects perform worse on average than in the ungloved condition, but the variation in relative performance is large for all conditions. The most drops occurred when ungloved, and the least with the vinyl gloves.

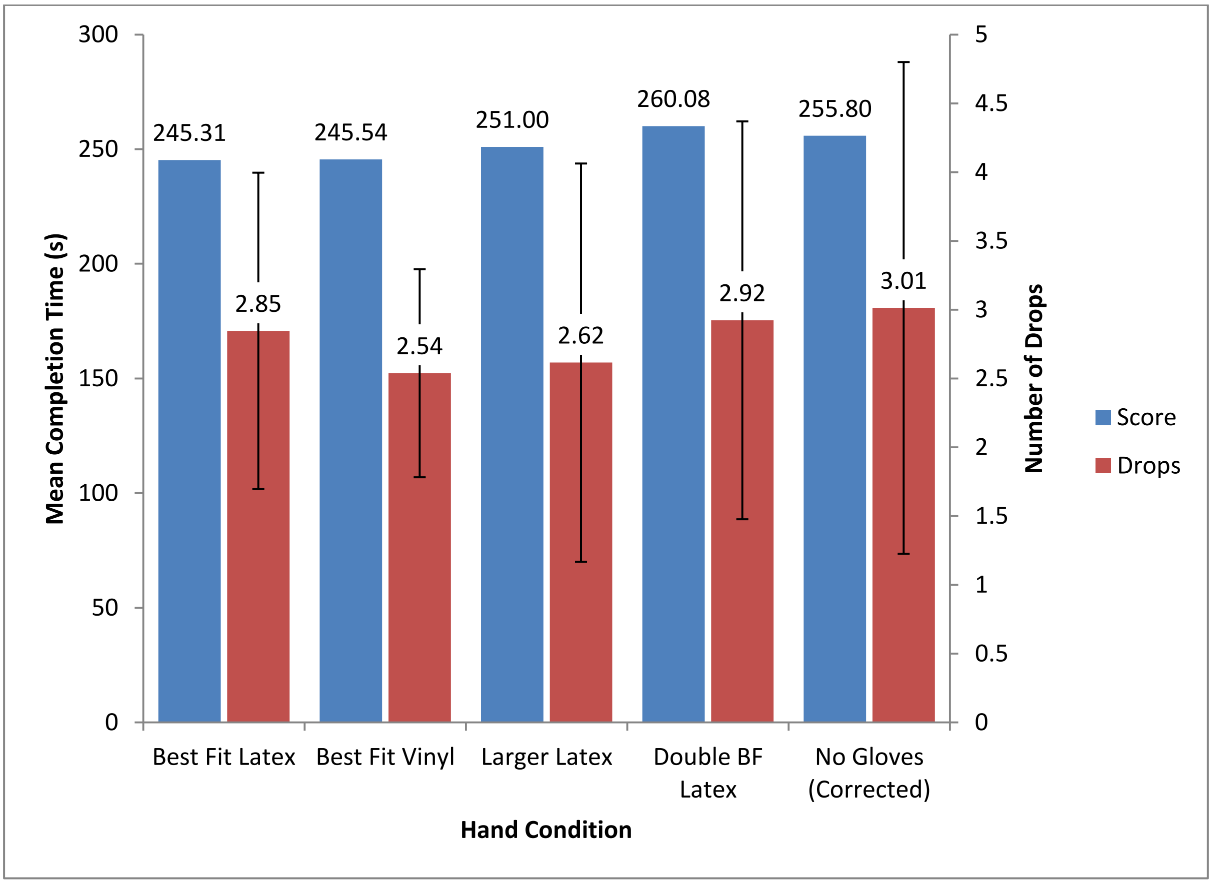


Figure 40. Comparison of Hand Conditions for Crawford – 'Pins and Collars' Test

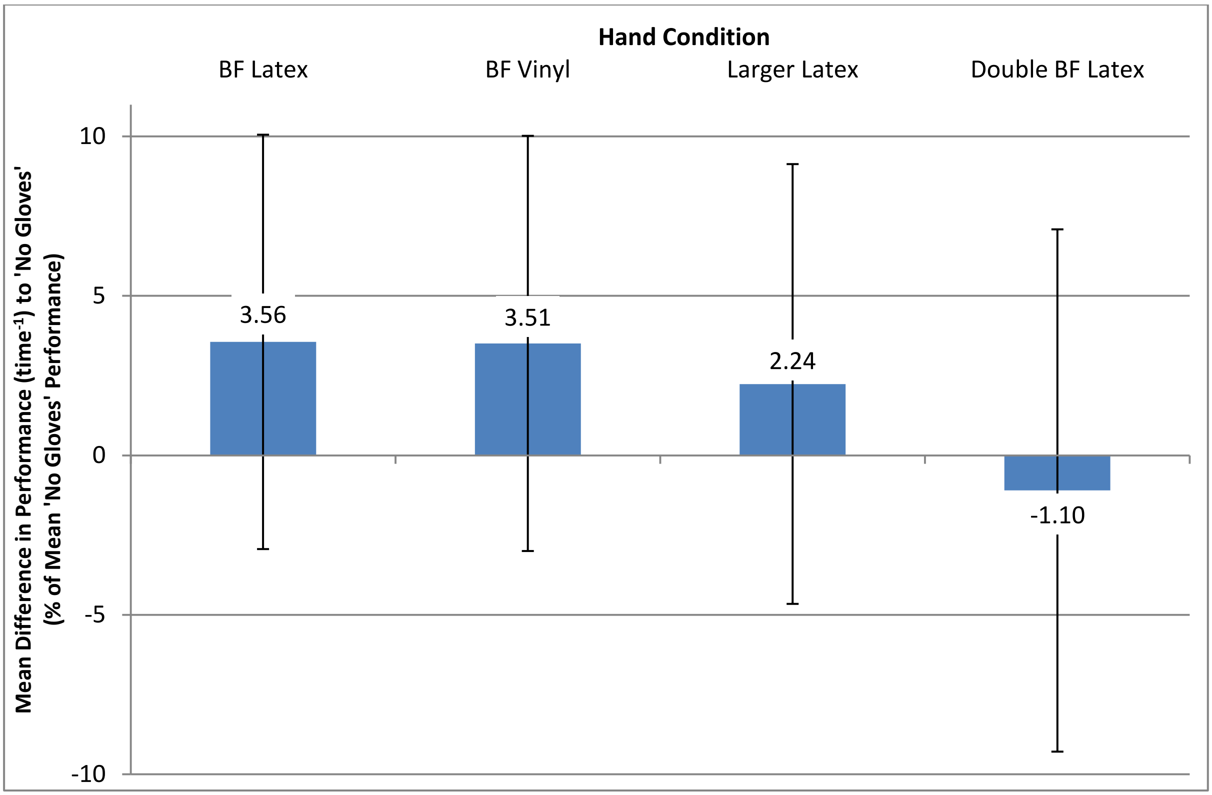


Figure 41. Comparison of Crawford – 'Pins and Collars' Test performance (time^{-1}) for different gloved conditions with corrected 'No Gloves' condition (with 95% confidence intervals)

None of the data showed significant non-normality (p≥0.072). Repeated-measures ANOVA for hand condition did not show any significant differences between hand conditions (p = 0.164). Furthermore, there were significant differences between *subjects* in the mean percentage of 'No Gloves' score across the four gloved conditions when compared to within-subject variation between *hand conditions* (p=0.09) i.e. the variation between subjects was more marked than the variation between hand conditions. Hand condition was also not a significant factor in the number of dropped parts in each test (p=0.703). In other words, the results found no consistent effect of hand condition on performance.

Tests were also carried out by Tasron [160], with the assistance of the author, on 25 students using Indigo nitrile examination gloves and varying the size. The method was altered to measure the number of pins and collars placed in two minutes. The results were analysed independently by the author. They showed no significant differences (p=0.375) in a repeated-measures ANOVA between bare-handed and gloved conditions or with varying glove fit. The mean scores and relative performance of gloved conditions to ungloved are shown in Figure 42 and Figure 43.

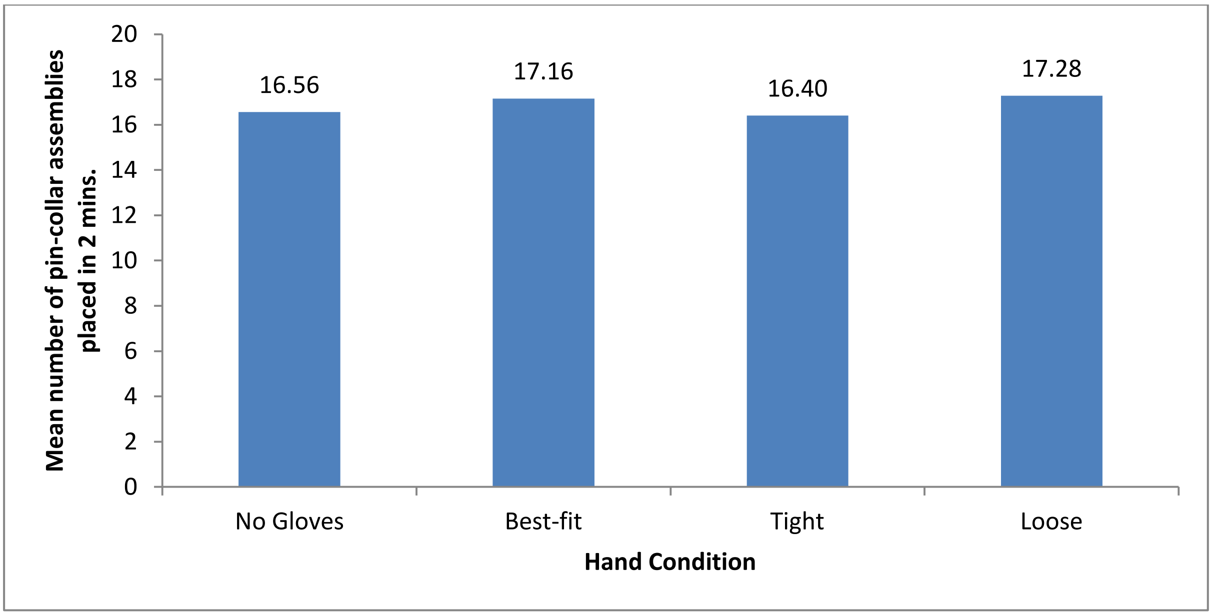


Figure 42. Results of Tasron's CSPDT 'Pins and Collars' experiment with nitrile gloves (n = 25)

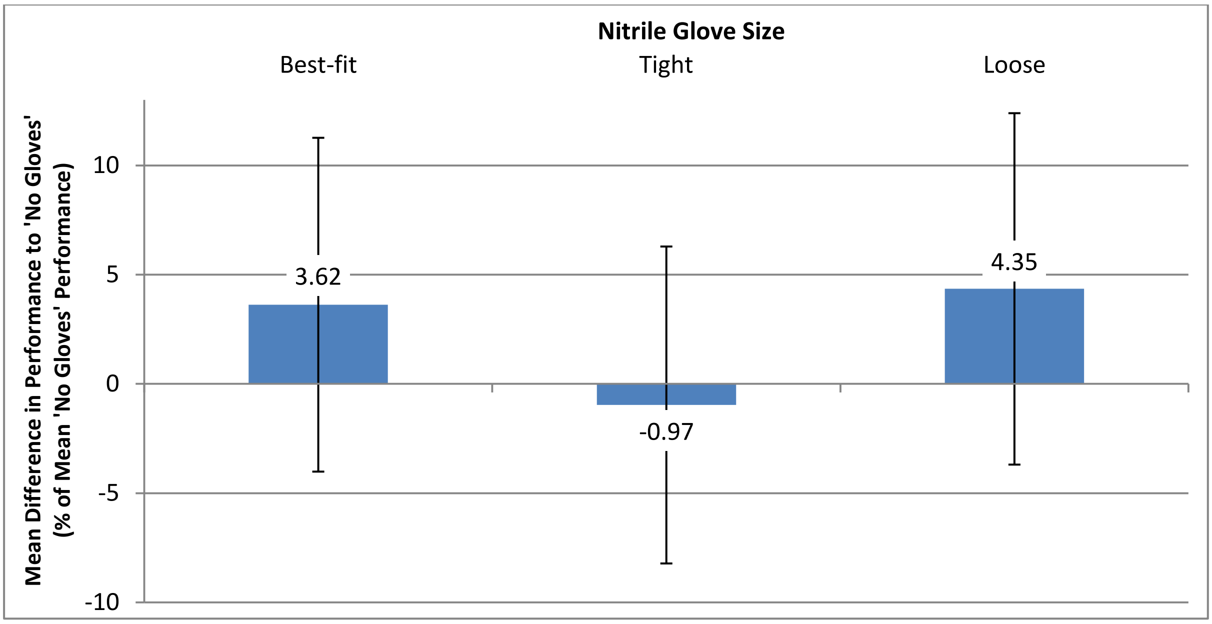


Figure 43. Mean difference of gloved conditions to the 'No Gloves' condition (% of mean 'No Gloves' performance) in Tasron's CSPDT 'Pins and Collars' experiment (with 95% confidence intervals)

6.4.3.'Screws' Results

Learning behaviour. There is a weak correlation (R^2 = 0.46) in the learning curve (Figure 44), but both the mean scores of the gloved tests and the single-subject ungloved tests show a reduction in completion time with repetition of the test. Since the extent of learning was unclear and a linear relationship could not be assumed, it was decided that the final 'No Gloves' score was a more reliable indicator of performance. As before, it was scaled to the average of tests 2-5 using the power curve equation (an increase of 7.5%, giving a mean completion time 4.2% less than taking the average of the two 'No Gloves' tests).

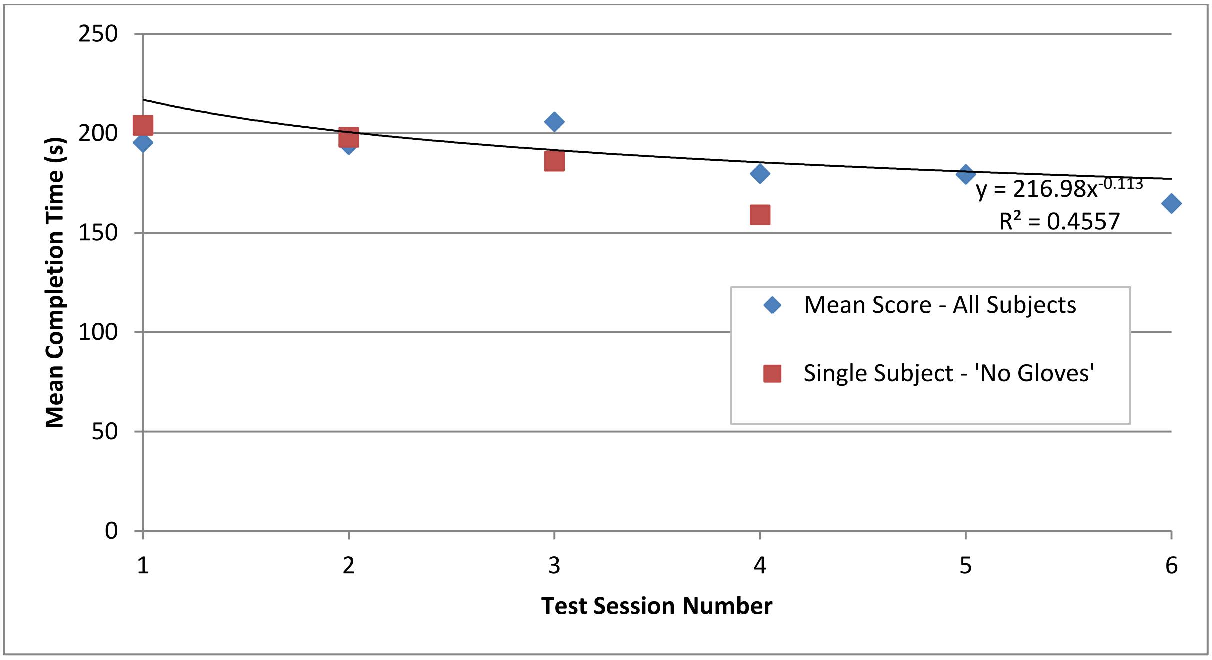


Figure 44. Learning behaviour for CSPDT 'Screws' test

Results. The results of the experiment are shown in Figure 45. The shortest mean completion time was achieved with the vinyl gloves, with the longest occurring with the double layer of latex gloves. The number of dropped parts followed a similar pattern, although more drops occurred in the ungloved condition than in any of the gloved conditions. The relative performance of the gloved conditions is compared in Figure 46.

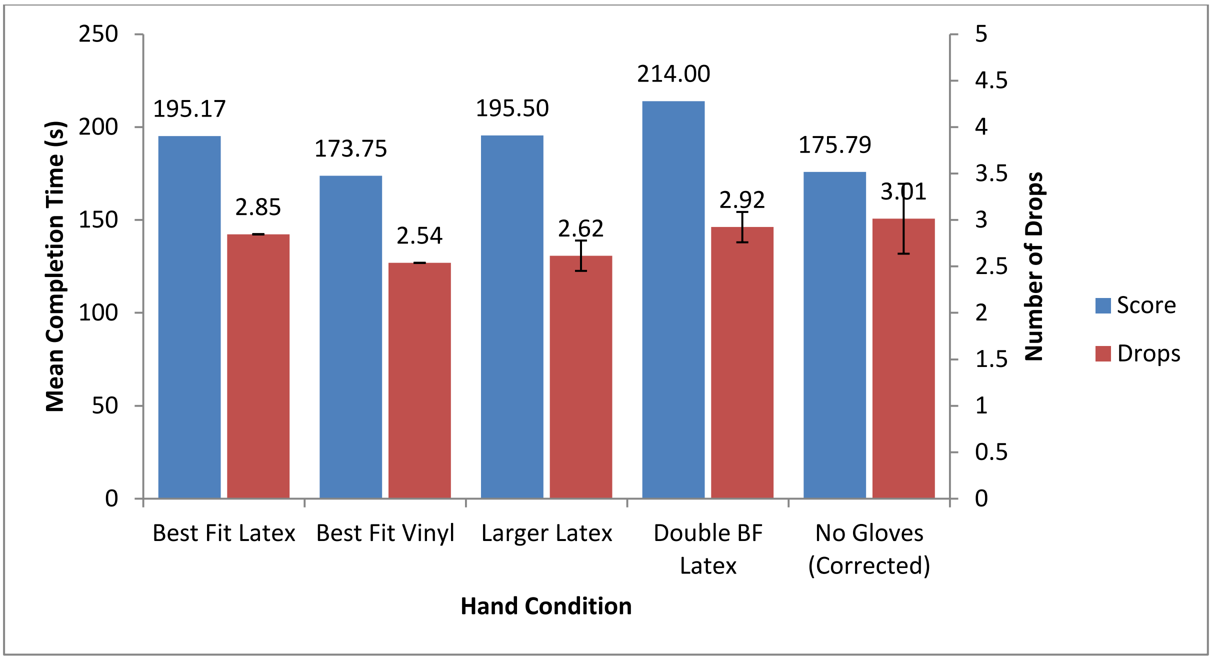


Figure 45. Mean completion time and number of dropped parts for five hand conditions in the CSPDT 'Screws' test (including 95% confidence intervals for the number of drops)

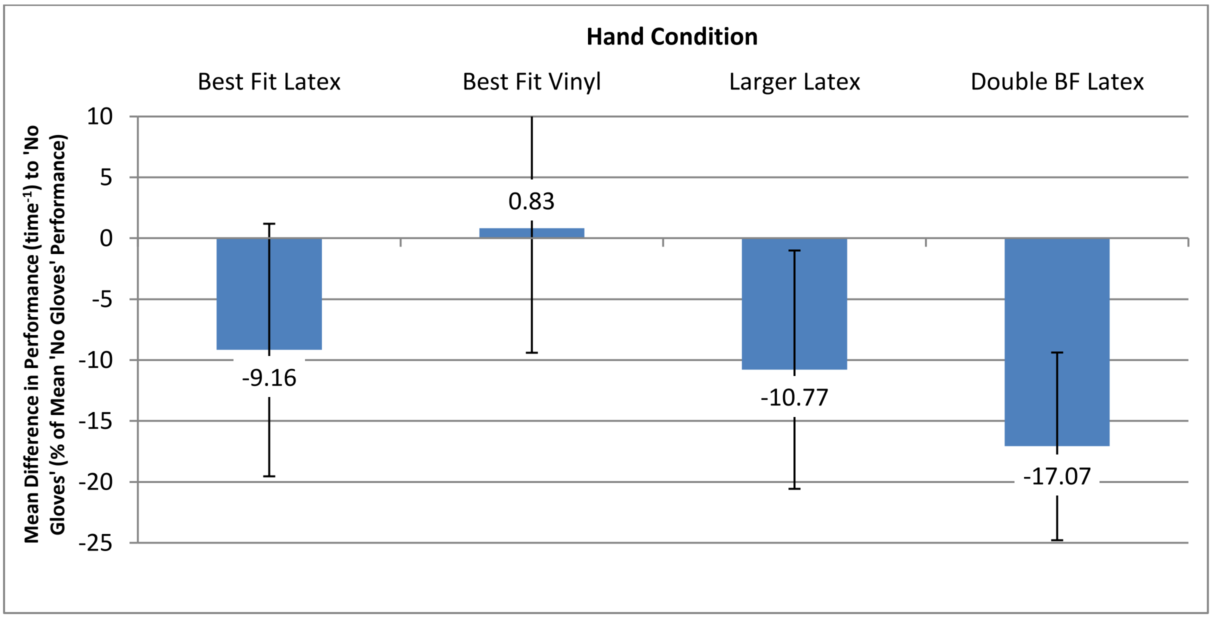


Figure 46. Comparison of Crawford – 'Screws' Test performance (time^{-1}) for different gloved conditions with corrected final 'No Gloves' condition (with 95% confidence intervals)

Hand condition clearly has some significant effect on performance time. Repeated-measures ANOVA (no results showed significant non-normality, $p \geq 0.166$) confirms that there are significant differences between the means ($p=0.001$). The results of the paired t-tests between the hand conditions are shown in Table 14, and Figure 47 is a schematic of the differences (N.B. due to overlapping, not all relationships could be displayed correctly).

Table 14. Paired t-tests for CSPDT 'Screws'

	Best Fit Latex	Best Fit Vinyl	Larger Latex	Double BF Latex
No Gloves	NS (0.058)	NS (0.900)	S (0.043)	S (0.001)
Best Fit Latex		S (0.009)	NS (0.896)	NS (0.173)
Best Fit Vinyl			NS (0.052)	S (0.004)
Larger Latex				NS (0.082)

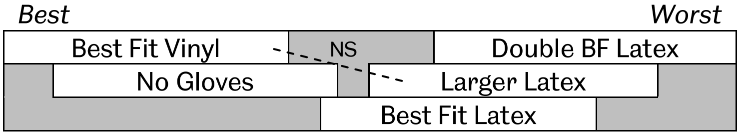


Figure 47. Schematic of differences between hand conditions for CSPDT 'Screws'

The 'Best-Fit Vinyl' and 'No Gloves' conditions clearly produce the best performance, the paired differences of both with the bottom three conditions having *p* values of less than 0.06 (four of six pairs being below the 0.05 significance level).

Tasron also included the 'Screws' test in her glove fit testing with Indigo nitrile gloves. The results, as analysed by the author, can be seen in Figure 48 and Figure 49. Repeated measures ANOVA of the results did not reveal any significant effect of wearing the gloves, or of glove fit (p=0.202).

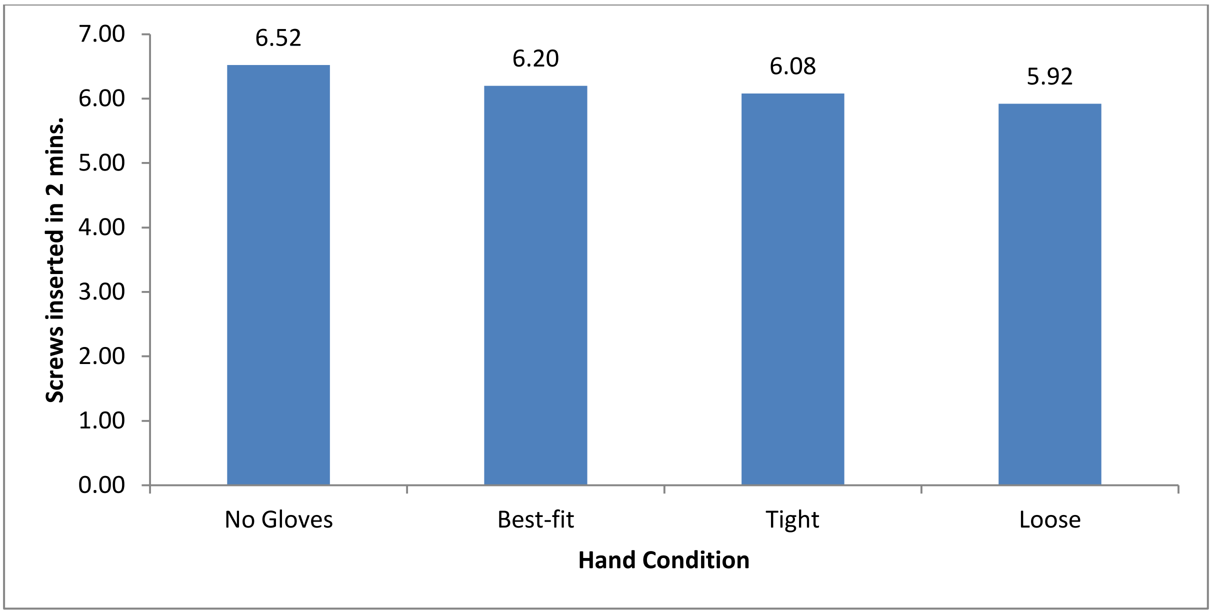


Figure 48. Results from Tasron's CSPDT 'Screws' experiment with nitrile gloves

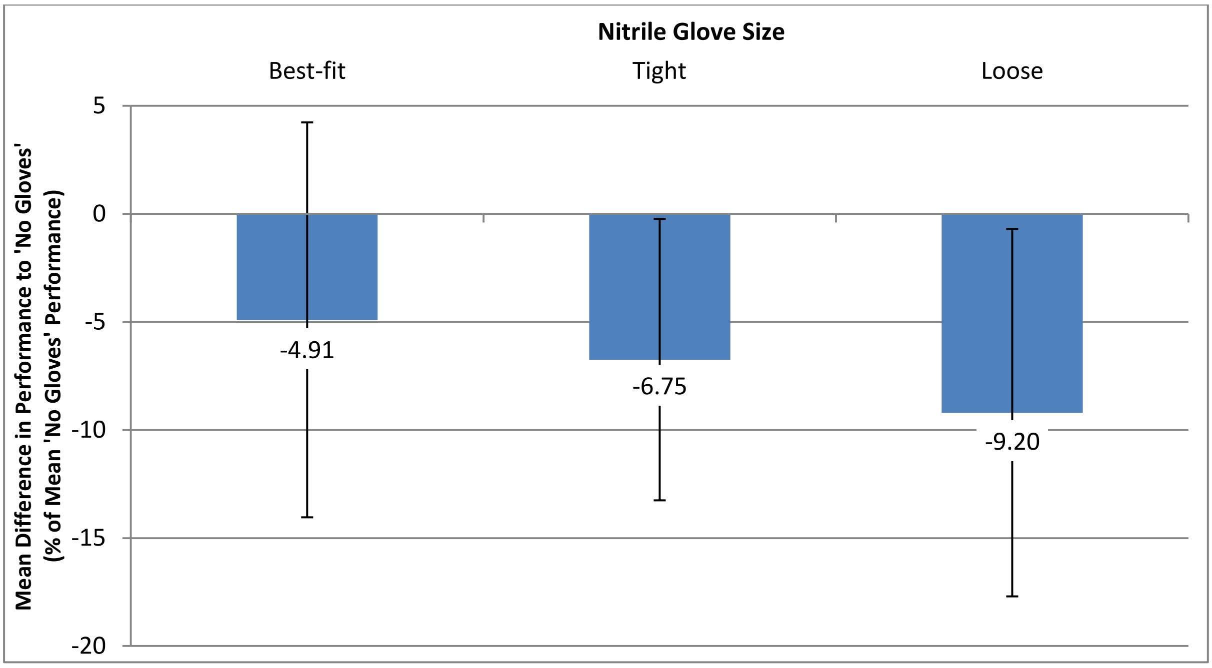


Figure 49. Mean difference of gloved conditions to the 'No Gloves' condition (% of mean 'No Gloves' performance) in Tasron's CSPDT 'Pins and Collars' testing (with 95% confidence intervals)

6.4.4. Discussion

Of the two parts of the Crawford Small Parts Dexterity Test, the 'Screws' test clearly discriminates best between hand conditions. No significant differences were found in two separate experiments in the ‘Pins and Collars’ test between ungloved and gloved conditions with various materials, fits and even with a double layer.

Participants’ comments after the ‘Pins and Collars’ tests were also mixed. Some found certain gloves to increase friction over the ungloved condition, while others found that the same glove reduced friction, and they disagreed on whether high or low friction was better for performance. Some commented that larger gloves made the task more difficult, while some said they made no difference. Similarly, some preferred the ‘No Gloves’ condition, with sweat generation in gloves being one explanation, while others felt that sweaty fingers reduced performance compared to dry gloves. Skin moisture content is clearly a factor in ungloved performance, and could contribute to the large variation between subjects. This could be improved with exfoliating and washing of hands before the test.

Latex and vinyl single-layer best-fit gloves performed very similarly (less than 0.1% difference), even though some felt the tweezers slipped more with vinyl and did not like the feel. Gripping pins with tweezers does not require large frictional forces or sliding motion, so frictional properties are probably less relevant than in other tests.

The double best-fit latex gloves did perform worst, however, and this is supported by comments made by a number of participants that double-gloving restricted movement, increased fatigue and made it harder to feel or to control muscles.

In the ‘Screws’ test, the vinyl gloves performed best and were significantly better than the single and double-layer latex gloves. On average, subjects completed the test two seconds faster with vinyl gloves than with no gloves, although the difference was not statistically significant. This result is surprising, but may show the importance of friction in the task, and that high friction is not always desirable. Many participants found the screwing part easier with vinyl because of the lower friction allowing the screwdriver to rotate whereas the latex gloves sometimes stuck to the screwdriver or to the screws when releasing them, but it was felt that the poor conformability of the vinyl made manipulation of the screw more difficult and the loose material sometimes caught when turning.

The same was true for both the double layer and the larger gloves, which performed worse, with loose material getting caught in the threads or on the screwdriver, meaning the technique needed to be adjusted. As previously discussed, this might not affect performance but may increase stress or discomfort. Both larger and double gloves reduced the perceived ability to manipulate the screws, whether due to loss of sensation, loose material or slipping of the two layers. Time was also wasted with the larger gloves in having to pull up the fingers to keep the glove material tight on the fingertips.

6.5. Bennett Hand-Tool Dexterity Test

6.5.1. Apparatus and procedure

The Bennett-Hand Tool Dexterity Test (as described in [60], and shown in Figure A 25) consists of: a wooden frame with twelve clearance holes of three sizes in each end; twelve sets of corresponding nuts, bolts and washers; two fixed spanners, one screwdriver and one adjustable spanner. In the original test, the bolt sizes are imperial (½" x 2 ¾", 5⁄16" x 2 ⅝" and ¼" x 2 ⅛") but the test was reproduced at the

University of Sheffield using metric measurements (M12 x 60, M8 x 50, M6 x 60). The two larger sizes are hex bolts, while the smallest have a slotted head for a flathead screwdriver. At the start of the test, the nut-bolt-washer sets are assembled in the holes at one end. The subject is required to remove, relocate and re-assemble the sets in the corresponding holes at the opposite end, using the adjustable spanner and the appropriate fixed spanner or screwdriver for the initial loosening and final tightening, and doing the rest by hand. The time to complete the task is recorded.

Initial testing found that the whole task was taking up to twelve minutes without gloves. By this point, hand fatigue was fairly severe. Besides the effect of hand fatigue, it was not felt that having multiple bolts of each size added to the information gained in the test. It was therefore decided to reduce the task to one set of each size. In the original test, the bolts were replaced in the same orientation, but it was decided to reverse them so that the test could easily be repeated by turning the rig 180°.

With the assistance of the author, Tasron tested 25 subjects in four treatments: ‘No Gloves’, ‘Best-Fit Nitrile’, ‘Tight Nitrile’ and ‘Loose Nitrile’ (see Section 8.2.3 for further details of the test procedure).

6.5.2. Results

The results, displayed in Figure 50 show that the shortest mean completion time was achieved with nitrile gloves that are tighter than the ‘best-fit’ size as chosen by the subjects, while on average subjects took the longest when ungloved.

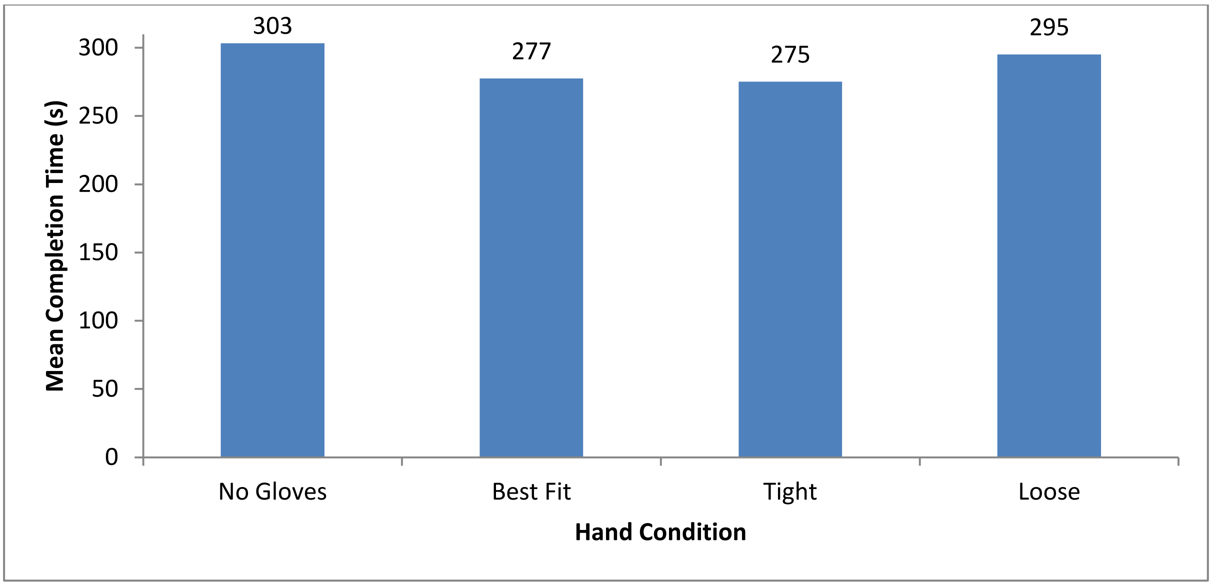


Figure 50. Results of Tasron's Bennett H-TDT experiment with nitrile gloves

A comparison of the performance of the gloved conditions relative to the 'No Gloves' score for each candidate, with 95% confidence levels, is shown in Figure 51.

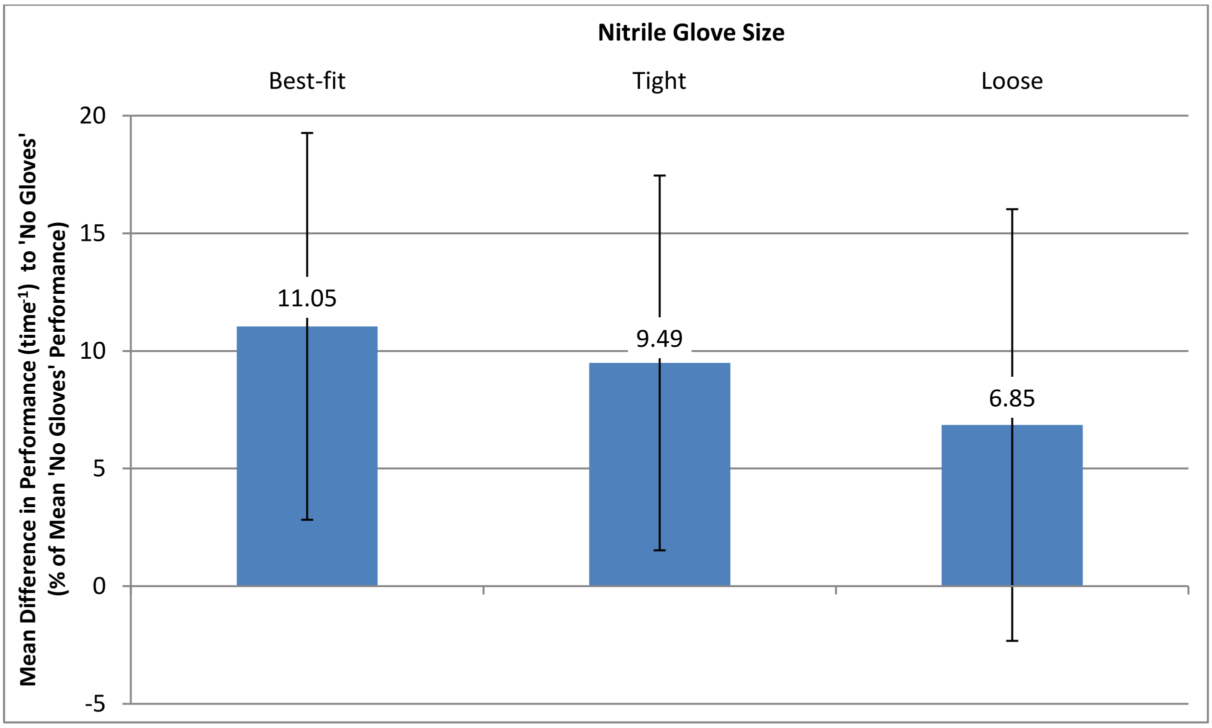


Figure 51. Comparison of performance relative to the ungloved condition in Tasron's Bennett H-TDT experiment of nitrile gloves in three categories of fit (with 95% confidence intervals)

The results for all four treatments deviated significantly from normality ($p \leq 0.008$ in Shapiro-Wilk test), so the non-parametric Friedman test for significance was used. Hand condition was not found to have a significant effect on completion time ($p=0.062$), however the *p* value was close enough to the significance level to warrant performing paired tests. The Wilcoxon Signed Ranks Test found that the completion time with best-fit and tight nitrile gloves was significantly less than without gloves, but no other significant differences were found (see Table 15 and Figure 52).

Table 15. Paired t-tests for Bennett H-TDT

	Best Fit	Tight	Loose
No Gloves	S (0.014)	S (0.022)	NS (0.484)
Best Fit		NS (0.677)	NS (0.288)
Tight			NS (0.258)

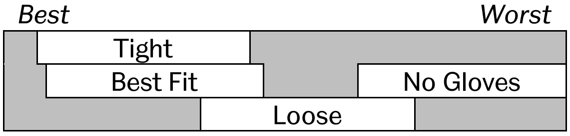


Figure 52. Schematic of significance for Bennett H-TDT results

6.5.3. Discussion

The most striking result of the Bennett Hand-Tool Dexterity Test experiment is that subjects performed worse on average with no gloves on than with nitrile examination gloves of any size. This would be difficult to explain were it not for the fact that the task was always performed first without gloves. While this allows a more consistent comparison of the gloved conditions with the ungloved across all subjects than including the ungloved condition in the randomisation of test order, the learning behaviour of subjects means that their first test is likely to be significantly worse than later ones. If the order of tests had been recorded, learning behaviour could have been estimated as in previous sections, but this data was not available to the author. However, it is reasonable to suggest that learning is the primary reason for poor performance in the ungloved condition.

It could also be that the gloves improved grip. Preliminary tests by the author using fat to lubricate vinyl examination gloves found an increase of 60% in completion time compared to the dry gloved condition. This would indicate that grip is a key factor in performance in the test. This hypothesis could be explored in further study.

The size of glove appeared to have little or no effect on the performance. Subjects rated the hand conditions out of ten in terms of hand fatigue felt after the test, and best-fit gloves rated much lower in this regard (3.48) than the tight (4.76) or large gloves (4.68). It may be that subjects were able to adjust to difficulties with the gloves so as not to affect performance, but suffered more from hand fatigue because of the adjustments. However, more objective analysis of fatigue would be necessary to make these assertions with any confidence. Overall, given the probable learning effects, this test does not appear to be a good indicator of the effect of examination gloves on dexterity.

6.6. Suturing Test

6.6.1. Research and apparatus selection

One suturing test [53] has already been considered (see Chapter 3). However, a plastic sheet was used in this method, which does not replicate the properties of human tissue well. Simulation of surgical suturing is required in a number of contexts. The most obvious one is training of medical or dental students. The Basic Surgical Skills course of the Royal College of Surgeons uses a multi-layered skin pad

[161] (Figure 53) that aims to replicate the elastic properties of the epidermis, dermis and fat layer. It has also been used in surgical skills testing [162]. While this model is undoubtedly realistic, the unit cost is prohibitive for large-scale glove testing. Dubrowski et al. [163] used an "artificial artery model resembling real tissue" to assess surgical skill, but no further details of the rig are given.

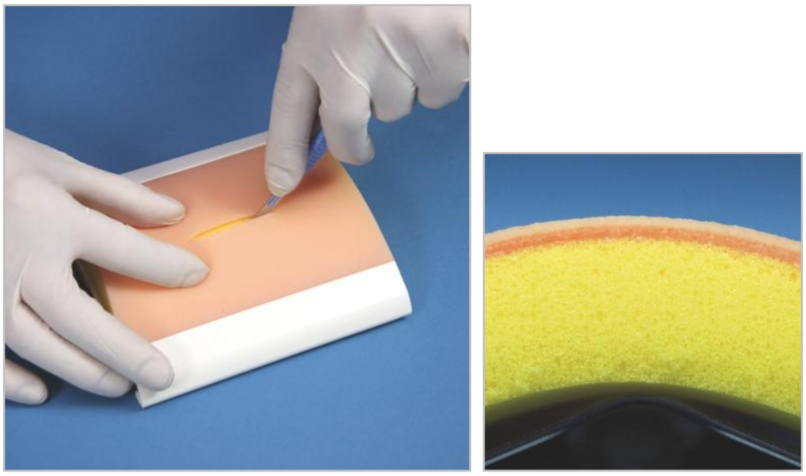


Figure 53. Skin Pad top view and cross-section (reproduced from [164])

For knot-tying practice alone, besides more coarse rope-tying tests such as the one discussed in Chapter 3 [102], surgical simulations have been developed such as the one included in the aforementioned Basic Surgical Skills course. These involve threading suture material through a magnetic weight and tying a knot while attempting not to lift the weight from the surface of the rig (simulating the need to avoid tearing tissue in a real operation). This adds a level of realism to the task, but is again a fairly expensive arrangement.

Other common and cheaper practice materials include orange or banana skins [165] and meat [166], however these have the disadvantages of being messy and inconsistent in mechanical properties.

A simpler technique is used in the School of Dentistry at the University of Sheffield for training undergraduate dentists (Figure 54). A sheet of rubber dam (a sheet placed in the mouth to prevent debris falling down the throat) is stretched over a plastic pot using a rubber band. The bottom of the pot can be attached to a fixed surface using sticky Velcro® pads, allowing limited movement to simulate real tissue operating conditions. An incision is then made in the rubber dam and the student attempts to close the incision by suturing. Because of the cost considerations, and because medical professionals who had used the rubber dam rig were satisfied that it allowed for a fairly realistic simulation of tissue surgical suturing, it was decided to use this apparatus.

Figure 54. Suturing test

6.6.2. Procedure design

Suturing requires three basic surgical tools: needle holders, tissue forceps and scissors, as well as the needle that is included in each pack of suture material. These are shown in Figure 55. A curved needle is generally used, which comes attached to a length of silk, nylon monofilament or other material. In basic suturing (suturing at depth is different), the needle is passed through the top of the tissue and out of the side of the opening. It is then passed through the other side and out the top. Tissue forceps are used to grasp the tissue when inserting the needle. The thread is then pulled through to leave a short amount protruding from the other side.

There are two basic suture patterns – continuous and interrupted. Continuous suturing is somewhat like conventional sewing, where the suture material is knotted only at the beginning and end of the opening, so that the suture material forms one continuous thread. In interrupted suturing, the suture is tied and cut after each pass across the opening, leaving a number of individually tied sutures. This requires more suture material than continuous suturing and takes more time.

Figure 55. Equipment used in suturing: (a) needle holders, (b) tissue forceps, (c) scissors and (d) curved needle

There are also two basic styles of knot-tying: instrument and hand tying (which can be one- or two-handed, but one-handed is most common). In instrument tying (shown in Figure 56), the long end is wrapped around the needle holders (usually twice the first time) and the short end grasped in the tip and pulled through the loop or loops, creating a ‘throw’ which is pushed down while the thread is pulled tight. This is then repeated, crossing the hands over each time. The number of ‘throws’ can vary depending on the surgeon, but four square knots is standard practice. The suture is then trimmed using the scissors (usually by an assistant).

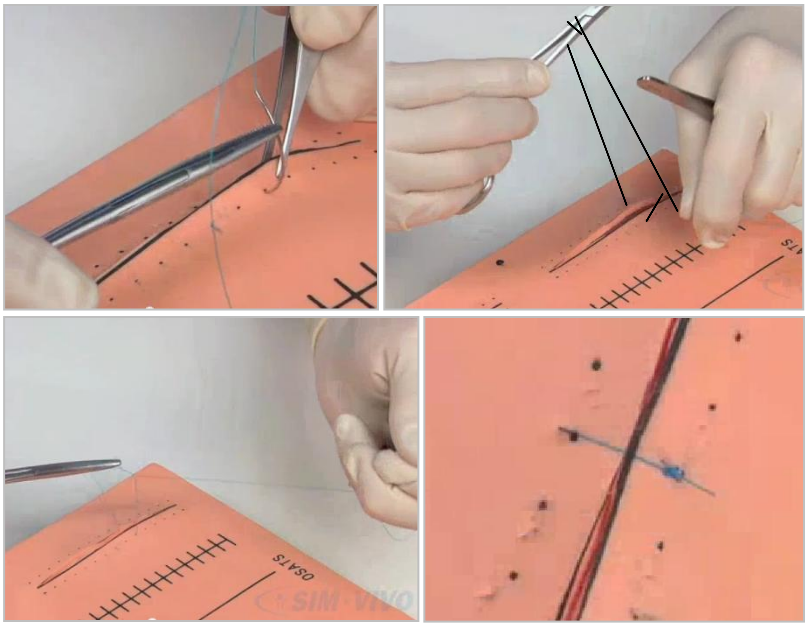


Figure 56. Suturing and instrument tying (stills reproduced from [167], lines darkened for clarity)

In hand tying (one-handed), one end is held tight using a hand or needle holders, while the other hand manipulates the thread. The technique is too complicated to describe, but is shown in Figure 57.

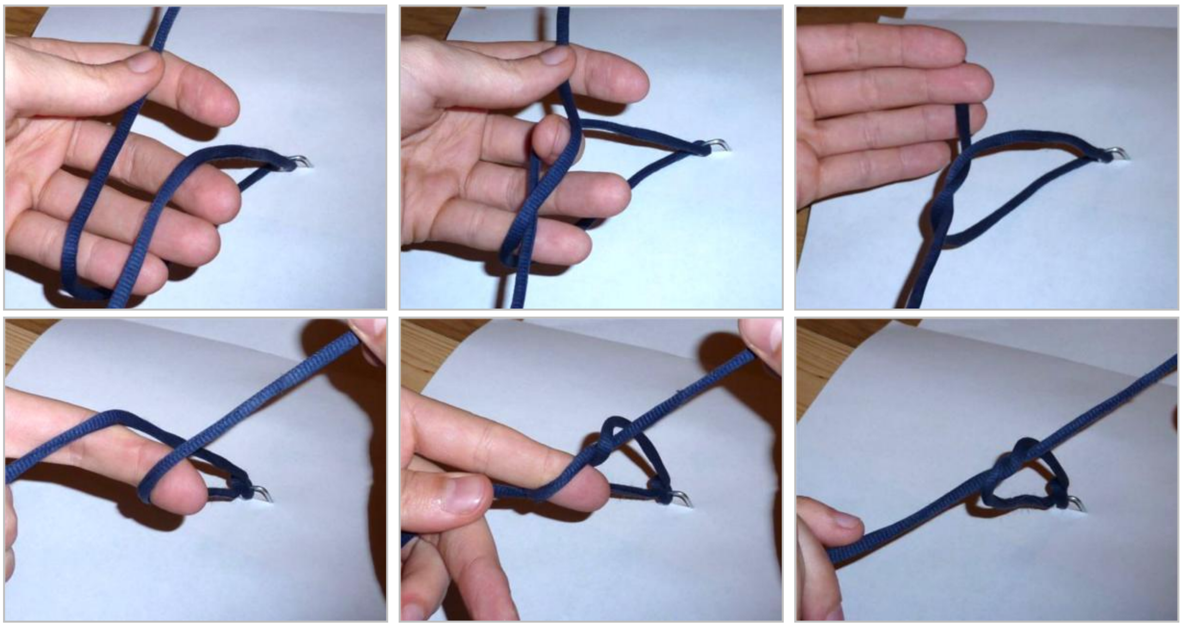


Figure 57. One-handed tying technique (reproduced from [168])

Hand tying requires more dexterity than instrument tying, takes longer and uses more suture material. Because of the complexity of hand tying, inexperienced surgeons tend to be more familiar with instrument tying. Since time, participants and suturing material were all limited, the instrument tying technique was selected for the testing. Interrupted sutures were preferred to continuous suturing as the knot-tying element was thought to involve the most dexterity.

6.6.3. Procedure

For further details of the experimental design, including participant recruitment, glove selection, location, perception scoring and fit measurement, see Section 6.2.3.

A fresh sheet of rubber dam was stretched over the pot, the tension being made as even as possible across the surface. Three incisions were made using a scalpel, each approximately 40 millimetres long and equally spaced around the pot. The pot was attached to a table using the Velcro® tabs. Because the location varied and was often improvised while participants waited to go into surgery, the height of the table and seat were not always ideal (for example a coffee table and sofa). The three instruments shown in Figure 55 were placed on the table along with a sachet containing a single silk suture (Ethicon MERSILK, size 3-0). The subjects were allowed to remove the suture and grasp it with the needle holders. They were instructed to place four interrupted sutures in one of the incisions using instrument tying, and were told that this would be timed, but asked to perform as they would in normal operating conditions. They were allowed to use as many 'throws' as they felt appropriate, but were asked to be consistent throughout the tests. The timer was started when they began the first suture and finished when the final suture was cut.

6.6.4. Results

The mean completion times for the 18 participants in the suturing test when ungloved and when wearing latex and nitrile examination gloves are shown in Figure 58. The fastest mean completion time was achieved with nitrile gloves, with the slowest being achieved with latex gloves, taking on average 5.4% (6.78 seconds) longer.

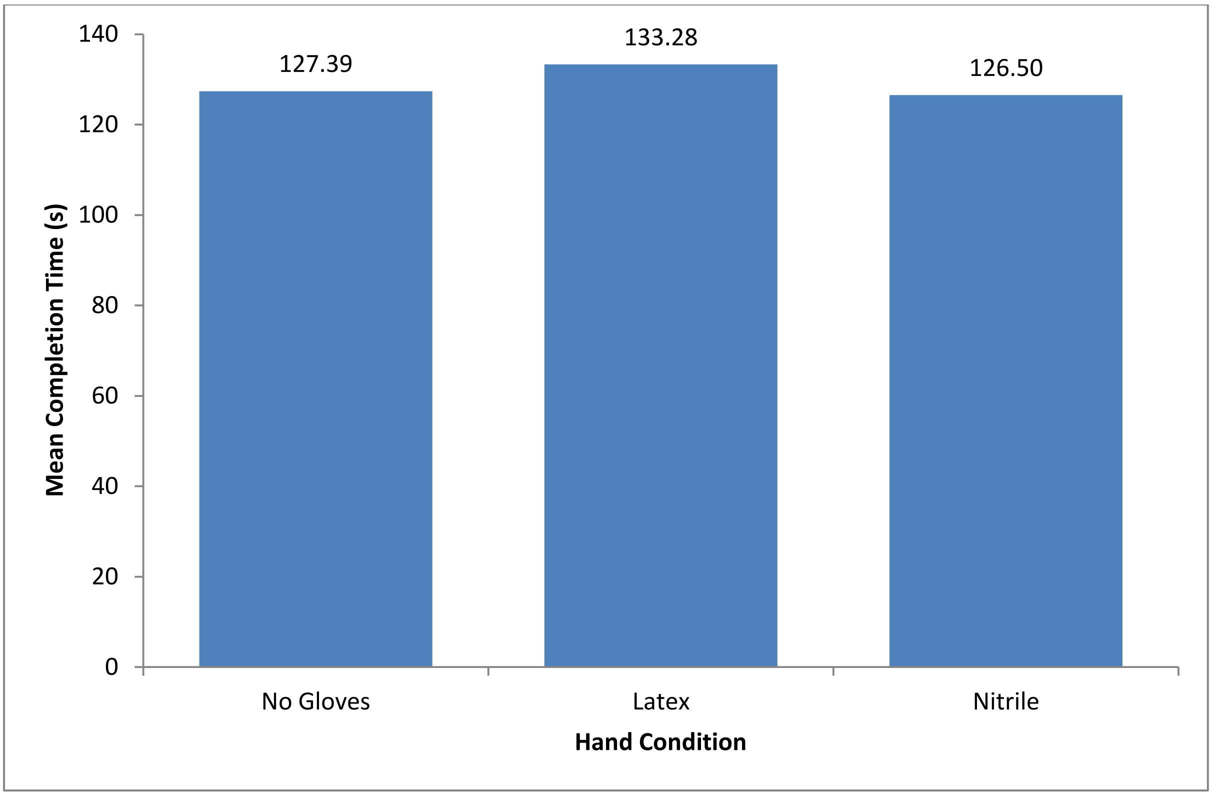


Figure 58. Mean completion time for three hand conditions in the suturing test (n = 18)

The relative performance of the two gloved conditions to the ungloved condition is shown in Figure 59 with 95% confidence intervals. It can be seen that the confidence intervals are large in comparison to the mean differences between all three conditions, suggesting that the probability of all three means being equal is high.

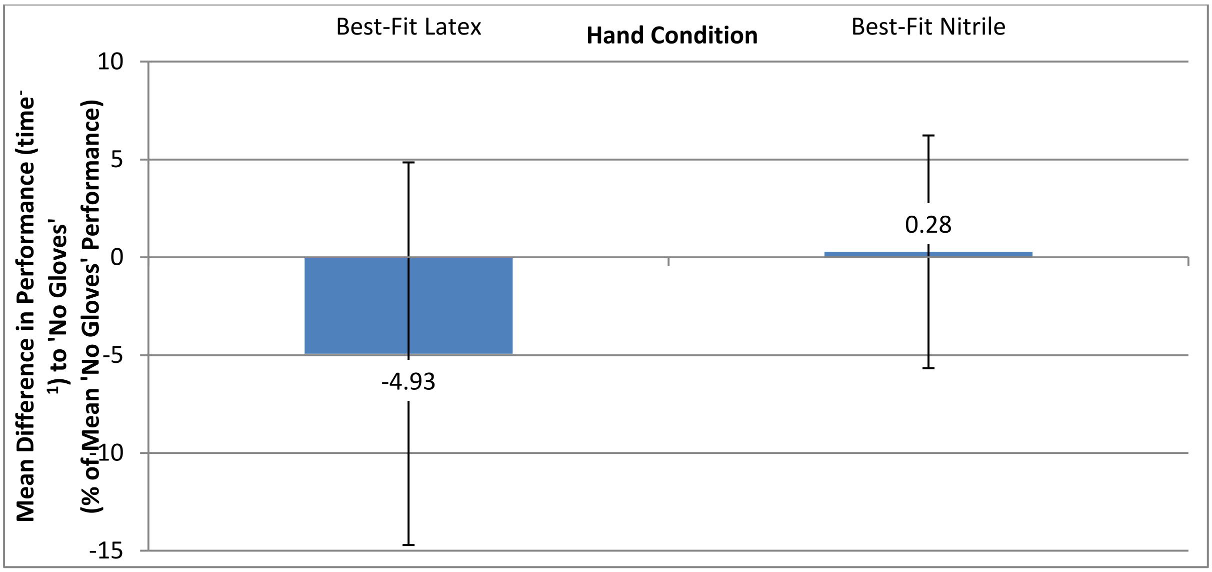


Figure 59. Comparison of performance (time^{-1}), relative to the ungloved condition, of latex and nitrile examination gloves in the suturing experiment (with 95% confidence intervals)

None of the three conditions showed significant deviation from a normal distribution ($p \geq 0.366$), but, as expected, repeated-measures ANOVA found no significant effect of hand condition on performance ($p = 0.374$).

6.6.5. Discussion

Although the test is still in the early stages of validation, it does not show promising discrimination between glove types or even between gloved and ungloved performance. However, suturing was identified as one of the common tasks that practitioners felt were adversely affected by gloves (see Section 4.4.3), and there were significant differences in perceived performance (see Chapter 10).

These perceived differences may relate to real performance differences that are not being measured or may be purely subjective, either an indication of the effect of the gloves on confidence or comfort or a result of preconceptions about gloves. If there are real performance differences, either the test does not have sufficient accuracy and resolution to bring them out, or it is not measuring the relevant performance outcomes.

Khan et al. [162] used a number of measures when assessing suturing performance, including: tissue and instrument handling and confidence; dimensions and orientation of sutures; appearance and economy of motion. They were able to find significant differences between grades of practitioners. However, this approach required videotaping and observation by three experts, which is time-consuming and difficult to do on a larger scale with non-surgical researchers.

Improvements to the test procedure could yield better results in separating the glove types. Hand tying of the sutures would increase the dexterity requirements and could magnify any differences that exist. The number of sutures could be reduced to compensate for the increased test time. It was also noted by one surgeon that difficulties in suturing and differences between gloves become more apparent in real operating conditions because of lubrication of the gloves and sutures with bodily fluids. This element could be introduced to the test by coating the gloves in lubricants such as water, artificial saliva or fat.

6.7. Analysis

6.7.1. Evaluation of the tests

Four dexterity tests were trialled with examination gloves: the Purdue Pegboard Test ('Combined' and 'Assembly'), the Crawford Small Parts Dexterity Test ('Pins and Collars' and 'Screws'), the Bennett Hand-Tool Dexterity Test and a new suturing test. The statistical significance of differences between hand conditions in each test are compared in Table 16.

Only the CSPDT ‘Screws’ test found a significant difference between two glove materials (latex and vinyl) in comparable conditions. The ‘Pins and Collars’ part of the test found no significant effect of hand condition, despite testing double-layered and loose-fitting gloves. The suturing test also found no significant effect of hand condition, but only tested well-fitting single-layer gloves and the ungloved condition so a direct comparison is difficult. The Purdue tests both found a significant effect for hand condition, but the performance difference between the gloves was clearer with the ‘Assembly’ test than the ‘Combined’ test. The Bennett Hand-Tool Dexterity Test only found significant differences with the ungloved condition, and this may have been a result of the ungloved tests being done first, although the loose condition was only one size larger than best fit, compared to two for the Purdue and CSPDT.

Table 16. Comparison of dexterity tests

Test	**Best-fit gloves paired difference *p* value**	**ANOVA/Friedman *p* value**
Purdue Combined	0.951	**0.002**
Purdue Assembly	0.256	**0.000**
CSPDT ‘Pins and Collars’	-	0.164
CSPDT ‘Screws’	**0.009**	**0.001**
Bennett H-TDT	- (nitrile only)	0.062
Suturing Test	-	0.374

6.7.2. Effect of medical gloves on dexterity

There was no consistent effect of wearing gloves or of glove material on dexterity across the tests. The ranking of hand conditions in terms of mean performance in each test is shown in Table 17. In two of the tests, ungloved performance was the best, in two more it performed worse than all best-fit gloved conditions, and in two it was better than latex, but worse than the other (nitrile or vinyl). In terms of glove material, latex ranked higher than vinyl in two tests, and lower in two others, while nitrile outperformed latex in the suturing, but not significantly.

However, where a double layer of latex gloves was used (Purdue and CSPDT), performance was worse than with a single layer in all tests. The same is true for larger glove, compared to those selected as the best fit.

Table 17. Ranking of hand conditions in dexterity tests

	Purdue (Comb.)	**Purdue (Assem.)**	**CSPDT (P&C)**	**CSPDT (Screws)**	**Bennett H-TDT**	**Suturing Test**
1	**No Gloves**	**No Gloves**	**BF Latex**	**BF Vinyl**	**Tight Nitrile**	**BF Nitrile**
2	**BF Vinyl**	**BF Latex**	**BF Vinyl**	**No Gloves**	**BF Nitrile**	**No Gloves**
3	**BF Latex**	**BF Vinyl**	**Larger Latex**	**BF Latex**	**Loose Nitrile**	**BF Latex**
4	**2 x BF Latex**	**2 x BF Latex**	**No Gloves**	**Larger Latex**	**No Gloves**	-
5	**Larger Latex**	**Larger Latex**	**2 x BF Latex**	**2 x BF Latex**	-	-

BF = Best-Fit

These results fit with what is already known about glove effects from previous research, as discussed in Chapter 2, as well as with comments made during the testing. An added layer reduces absorbs and distorts tactile feedback signals that are vital for fine dexterity, while loose material similarly reduces tactility, but also gets trapped, causing delays in performing fine manual tasks. The effects of gloves on tactility are explored further in Chapter 7.

The varying performances of glove materials and the ungloved condition in the tests may simply be due to statistical variation, since no significant differences were found for most of the tests, or it may be that different aspects of dexterity require different attributes. The two tests in which vinyl outperforms latex may benefit from lower friction, allowing pins to be released or a screwdriver to be turned more easily. The Purdue Assembly test requires fine finger dexterity and good tactile feedback, and so the ungloved condition performs best, and the close-fitting latex outperforms the less elastic vinyl (see Chapter 11 for testing of glove properties). In order to draw more firm conclusions about glove effects on dexterity, it is necessary to understand other factors such as their effect on tactility, their mechanical properties and the effect of glove fit. Further analysis will be left until Chapter 12.

6.8. Conclusions

Both parts of the Purdue Pegboard Test found a significant effect of hand condition on performance, but no significant differences could be found between glove types (latex and vinyl examination gloves). Because of the agreement of the results and the similarity in methods between the two parts, the 'Combined' test was felt to be redundant and it was recommended that only the 'Assembly' test be used for glove evaluation. Because of the relative coarseness of the test, testing on a larger sample size was recommended to increase the significance of the differences.

Two separate experiments using the Crawford Small-Parts Dexterity Test found no significant effect of hand condition on the 'Pins and Collars' score, but the 'Screws' part of the test produced significant differences between hand conditions, and showed a promising ability to discriminate between gloves.

The Bennett Hand-Tool Dexterity Test also found a significant effect of hand condition, with subjects performing worst when ungloved, but the results were affected by learning behaviour, and the test was not thought to be a good method of assessing glove performance.

A new suturing test did not find a significant effect of hand condition on performance. Improvements in the method were recommended, as well as testing in lubricated conditions, and with a larger sample size, to determine whether perceived differences in surgical suturing performance between gloves can be measured.

The most promising tests for evaluation of medical glove dexterity are the Purdue ‘Assembly’ test and the Crawford ‘Screws’ test. Validation of the tests with a larger sample size is recommended.

7. Tactility

7.1. Introduction

Tactility, or *cutaneous sensibility*, is the ability to sense external stimuli through the skin. In Chapter 5, three tests were selected for further testing and development with medical gloves: the Semmes-Weinstein monofilaments, the Roughness Discrimination Test, and Gnaneswaran's 'sponge and glue' test [53]. It was proposed that the development of the 'sponge and glue' test should include a subcutaneous stiffness element as well as the original surface irregularities. In addition to these existing tests, a pulse location simulation test was proposed, and a dental probe examination rig [158] was to be developed for use in a new test of tactility.

7.2. Semmes-Weinstein Monofilaments

7.2.1. Design of new rig

A number of issues were identified with the current Semmes-Weinstein monofilament test equipment and procedure, as detailed in Section 3.5. The main problem is with accuracy and repeatability of the applied force. Because of the nature of the FA I and SA I mechanoreceptors, which are particularly sensitive to edge effects, the level of stimulation can change depending on whether these mechanoreceptors encounter the edge of the filament. The applied force can also change dramatically depending on the friction conditions, since the end can be considered as either free or pinned, the difference theoretically changing the buckling force by a factor of 16. Furthermore, the applied force may be subject to dynamic effects, in which the buckling load can be exceeded if the force is applied too quickly.

The accuracy of the specified forces has also been questioned (e.g. [141, 143]) since the monofilaments are often manufactured to size specifications rather than being calibrated for force, and so variation in the properties of the nylon could affect the buckling load. Bell-Krotoski and Tomancik [143] also noted that the contact stress was almost impossible to calculate because of the bending of the filament, although none of the research done seems clear on whether stress or applied force correlate best with cutaneous stimulation. Since the diameter of each filament is different, this is an important question, since the applied stress may not correlate with nominal force. However, it may be that where the diameter of the filament is smaller than the spacing of the mechanoreceptors, the difference between force and stress becomes immaterial. Further work that is beyond the scope of this study would be needed to fully understand this area.

Lastly, the nature of the monofilaments means that the applied force varies in discrete amounts, which limits the resolution of the test. Since the differences in the effects of medical gloves on tactility may be very slight, they may be difficult to identify at the current resolution.

Some attempts have been made to solve the issues mentioned – notably the introduction of the Weinstein Enhanced Sensory Test (WEST), which has rounded ends and individually force-calibrated filaments to produce a more consistent buckling load. However, the WEST has a reduced number of filaments, so that the resolution is not as great as the original test. A solenoid-operated rig has also been designed [142] that allows automated, repeatable force application of the filaments to a consistent location, but does not address the issue of resolution. Another device has been patented [169] in which the force can be adjusted on a continuous scale, but must still be applied manually. A new design was proposed which combined previous ideas to produce a rig in which a variable force could be applied mechanically to a consistently located fingertip, using a single nylon monofilament. However, prototype testing found that the slenderness ratio of the filament (the ratio of length to diameter) was so high as to cause it to buckle under its own weight at the longer end, making it unusable.

7.2.2. Selection of rig and test procedure

Because of the issues identified with the design of a new rig, it was decided to carry out further testing using existing apparatus to determine the viability of monofilaments as a test method for medical gloves. Depending on the outcome of the testing, it may be appropriate to consider re-design again in the future.

As discussed, there are two basic monofilament tests currently available. The original Semmes-Weinstein Monofilaments consist of twenty separate handles with a single filament on each, while the WEST consists of two handles, each with five filaments on. It is claimed that the WEST has greater accuracy and repeatability, but it has a smaller range of filaments. Testing has also shown the Semmes-Weinstein test to be comparable with other available tests in terms of repeatability [143], and since the same filament set and operators will be used across the range of hand conditions for each subject, it was decided to use the Semmes-Weinstein Monofilaments to give greater resolution.

Apparatus. An example of the Semmes-Weinstein monofilament apparatus can be seen in Figure A 30. It consists of a plastic handle to which the monofilament is perpendicularly attached. There are twenty handles, each of the same length (approximately 40mm) and varying in diameter. They are each marked with a letter, from A to T, and a number representing the force level, which is calculated as follows:

$$Force\ level = log\ [buckling\ load\ (g) \times 10^4] \tag{1}$$

The force level ranges from 1.65 (A) to 6.65 (T), which corresponds to a range of 4.38 x 10^{-5} – 4.38 N in buckling load.

Procedure. The testing procedure used was the Rapid Threshold Procedure™ (from [141]), which seeks to determine the threshold force at which detection occurs fifty per cent of the time. The procedure is as follows:

1. Start well above the threshold and move down the force scale
2. Ensure the participant cannot see the filament
3. Apply the filament to the fingertip steadily (approximately one second each for application, holding and removing)
4. If the participant indicates that they detected the force, proceed to the next lowest force
5. At the first failure to detect, go back to the previous (higher force) filament and test again
6. If they fail to detect this filament, its value is the threshold (since they have once succeeded and once failed to detect it)
7. If they do detect it, move down to the previously-missed level and stimulate again
8. If they miss this level (for the second time) the threshold is taken as halfway between the higher, detected and lower, undetected values
9. If they detect this level, proceed to the next lowest level as if they had never missed it

Examples are shown in Table 18.

Table 18. Examples of the Rapid Threshold Procedure™ [141]

Level	Detected?
4.17	Yes
4.08	Yes
3.84	No
4.08	No

Threshold: 4.08

Level	Detected?
4.17	Yes
4.08	Yes
3.84	No
4.08	Yes
3.84	No

Threshold: 3.96

Level	Detected?
4.17	Yes
4.08	No
4.17	Yes
4.08	Yes

Continue to 3.84

7.2.3. Preliminary testing

Preliminary testing was carried out on two participants using a range of gloves in different sizes, and including double-gloving. The threshold force level varied from 2.005 (which is classified as a 'normal' level of sensation on the standard scale [170]) to 4.125 (which indicates 'diminished protective sensation' i.e. a reduction in ability to feel stimuli which may be causing injury).

The lowest threshold force for both participants was achieved with no gloves, with the highest being achieved with a double layer of gloves. In general, it was found that wearing extremely tight gloves increased the threshold, and wearing extremely loose gloves increased it further. The nitrile examination gloves performed worse than the latex and vinyl ones for both candidates. Surgical gloves, including the thinner Super-Sensitive and microsurgical ones, did not perform better than examination gloves.

It was found that, with loose gloves, it was necessary to pull the glove finger taut in order for the monofilament not to slip. It is recognised that this is not necessarily a realistic representation of performance, since the wrinkles in larger gloves can inhibit sensibility, but was necessary for the completion of the test.

7.2.4. Final testing

The Semmes-Weinstein monofilament test was included in Test Battery 1, in which postgraduate students were tested in a number of dexterity and tactility tasks. For further details of the experimental design, including participant recruitment, glove selection, location and fit measurement, see Section 6.2.2.

7.2.5. Results

The mean threshold forces for the five hand conditions are shown in Figure 60. Because of time restrictions on the testing, only 9 participants performed the test with all five hand conditions, with another 8 being tested with some hand conditions. The results of one participant from the preliminary testing were also added (the other participant also took part in Test Battery 1).

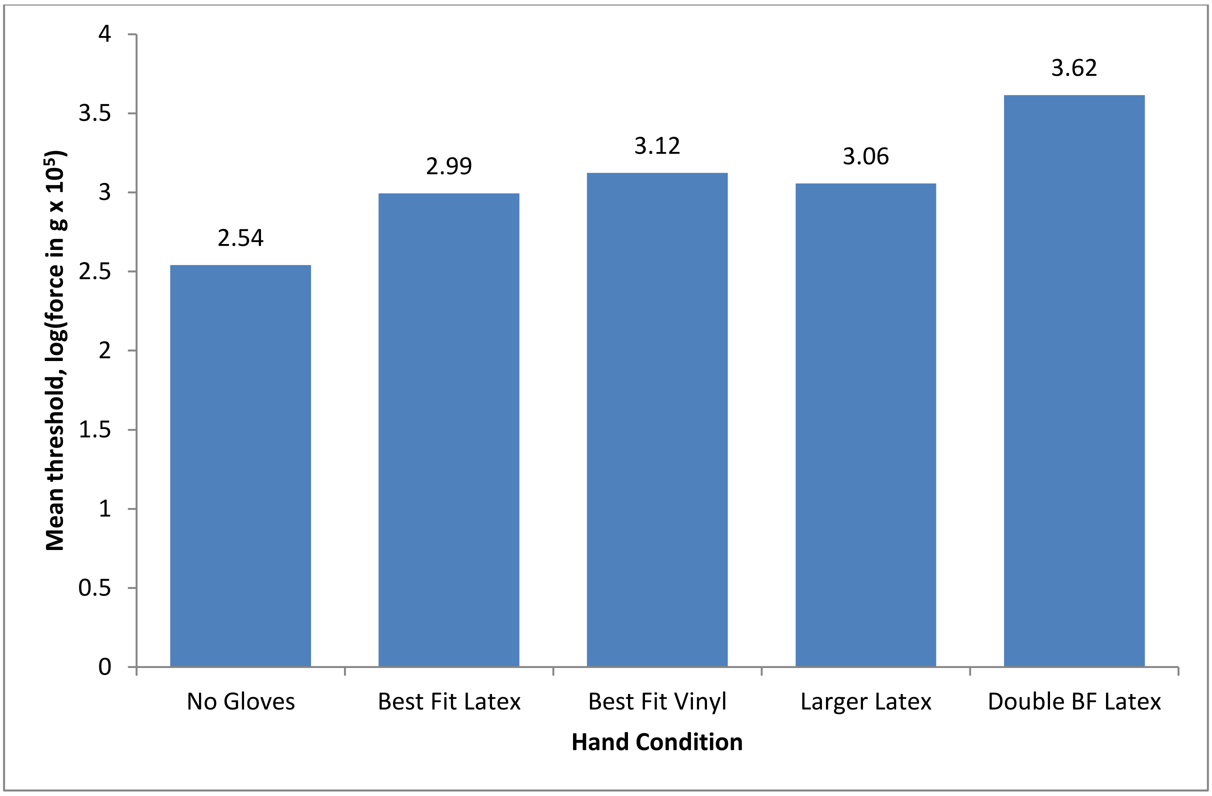


Figure 60. Mean Semmes-Weinstein Monofilament test scores (threshold log force) for five hand conditions (n=10)

It can be seen that the lowest mean threshold force, and therefore the best performance, was achieved in the ungloved condition, with the highest mean force being achieved with the double layer of gloves. This confirms the findings of the preliminary testing. Figure 61 shows the performance (defined as the inverse of threshold force level) of the four gloved conditions relative to the ungloved condition, with 95% confidence intervals.

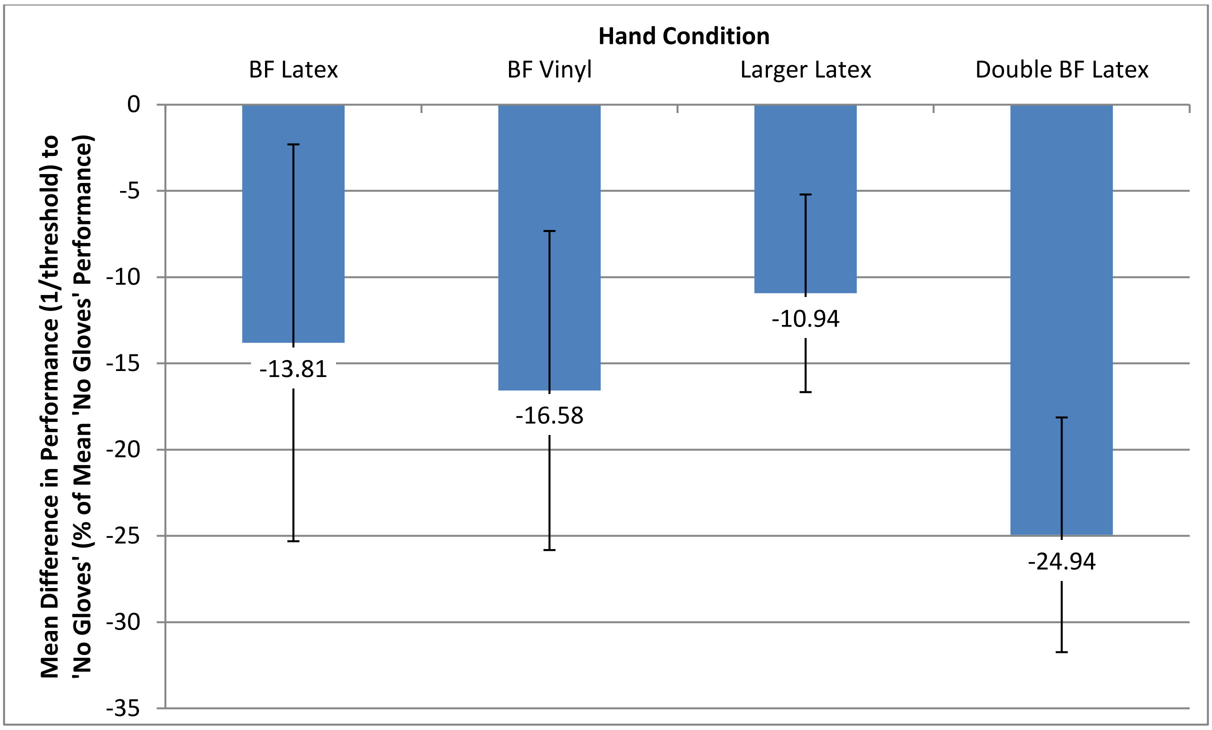


Figure 61. Comparison of differences to ‘No Gloves’ performance in Semmes-Weinstein Monofilament test for four examination glove conditions (with 95% confidence intervals)

Two of the results showed significant deviation from normality in the Shapiro-Wilk test. The Friedman non-parametric test for significance was therefore used. Hand condition was found to have a significant effect on threshold force (p=0.000). The Wilcoxon Signed Ranks Test was performed on pairs of hand conditions, and the results are shown in Table 19.

Table 19. Paired tests (Wilcoxon) for Semmes-Weinstein monofilament test results

	Best Fit Latex	Best Fit Vinyl	Larger Latex	Double BF Latex
No Gloves	S (0.006)	S (0.003)	S (0.003)	S (0.001)
Best Fit Latex		NS (0.553)	NS (0.964)	S (0.006)
Best Fit Vinyl			NS (0.823)	S (0.016)
Larger Latex				S (0.001)

Figure 62. Schematic of significance for Semmes-Weinstein monofilaments results

The mean threshold force for the ungloved condition was significantly lower than for all gloved conditions. The mean force threshold for the double-gloved condition was significantly worse than for all the single-layer, gloved conditions. However, differences in glove size and material did not produce significant differences in threshold force.

7.2.6. Discussion

The relative performance of the ungloved condition and the gloved conditions is unsurprising. The gloves create a barrier between the stimulus (the monofilament tip) and the mechanoreceptors that sense mechanical stimulation. The soft polymer of the gloves is likely to dampen the impact and to spread the load across a larger area. Increasing the thickness of the barrier (such as by double-gloving) will increase the damping.

It would also be expected that the loose material in larger gloves would distort the tactile cues and make detection of a stimulus more difficult. However, the results do not support this hypothesis. One possible explanation is the fact that the larger gloves were pulled flat on the fingertips in order for the filament not to slip. In medical practice, there will be significant movement and wrinkling of the gloves which will have an effect on tactility.

The lack of significant differences between gloves of different materials contrasts with medical practitioners' views (Chapter 4) that less flexible and conformable gloves reduce tactile ability. The mean number of force levels by which the two conditions differed was 0.3, and the resolution of the test is 0.5. (Where one level is detected both times and the level below is not detected at all, the threshold is taken as halfway in-between.) This presents some difficulty in finding a significant difference, since the expected threshold level will, as often as not, be the same for both conditions. A continuous scale, as proposed in Section 7.2.1, given a good level of accuracy, could provide a way to detect these finer differences.

Although the Semmes-Weinstein monofilaments test shows some ability to discriminate between hand conditions, the resolution needs improving for medical glove testing, and it would need to be supplemented with other tactility tests that create a more realistic tactile environment, recreating the real movement of gloves on the fingertips.

7.3. Roughness Perception

7.3.1. Introduction and previous testing

The standard Roughness Discrimination Test [137] consists of 69 cards on each of which four squares of sandpaper are mounted. Three of the squares are of one grade, and the fourth is of another. Subjects are required to run their finger across each square and identify the "odd one out". The test was trialled with a dental explorer, as per Wilson, Gound et al. [76], but the test length was found to be impractical.

Following this, modified roughness perception tests were carried out at the University of Sheffield [171] on nine undergraduate students, using two types of examination glove (PolycoHEALTHCARE Finex PF latex and Finite P Indigo AF nitrile) and ungloved. Instead of asking the subjects to correctly identify a difference in roughness, the aim was to quantify the perceived differences in roughness between sandpaper samples with a range of grit sizes. The procedure was adapted from [172], in which the test was carried out on paper samples, and is based on the magnitude estimation method, a form of psychophysical ratio scaling, described in [173]. Seven of the subjects used the standard dynamic technique – stroking the samples, while the remaining two used a static method, described below.

Procedure. Before the test, subjects were given verbal instructions in how to perform the test and in the method of magnitude estimation. The subjects sat at a table and were blindfolded. A cardboard guide was placed in front of them to allow them to locate the sandpaper (Figure 63). A randomly-selected sandpaper sample was placed in the guide, and the subject was instructed to feel the sample. In the dynamic test, this involved lightly placing their dominant index finger at the far end of the sample and drawing it slowly back towards themselves until they reached the end of the sample. In the static test, it involved pressing the fingertip onto the sample without moving it horizontally.

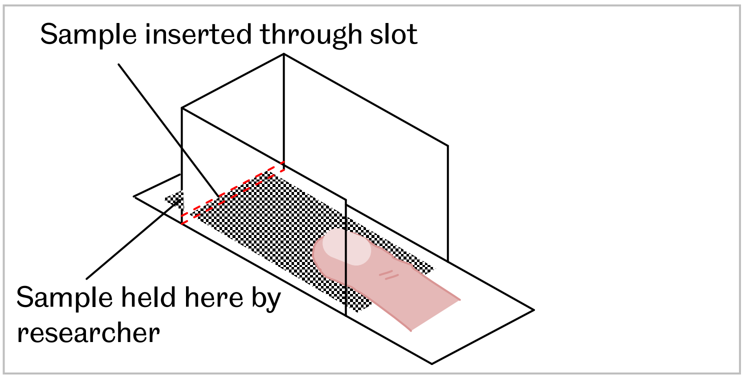


Figure 63. Roughness Perception Apparatus

For each sample, the subject was required to assign a numerical score that corresponded to the perceived magnitude of roughness. They were allowed to set their own scale from the first sample that was presented, with any positive, non-zero value being allowed. Subsequent samples were scored relative to previous ones, so that if a sample was twice as rough as the previous one, the score would be twice as high. The samples were presented in a random order, with each sample being presented seven times in total.

The whole test was repeated for each hand condition (in a random order), and subjects were instructed to maintain the same scale across all hand conditions to allow a fair comparison.

Sandpaper grades. Seven grades of sandpaper were used, with either aluminium oxide or silicon carbide grains on latex backing paper. The FEPA grit designations and average particle diameters are listed in Table 20.

Table 20. Sandpaper grades and particle sizes for roughness discrimination test

FEPA Grit Designation	Average Particle Diameter (μm) [174]
P40	425
P80	201
P120	125
P180	82
P240	53.5
P400	35 ± 1.5
P800	21.8 ± 1.0

The grades were chosen based on preliminary testing, and give a marginally smaller range than the 24-600 (16-715μm diameter) CAMI grades used in Nolan and Morris's Roughness Discrimination Test.

Friction measurement. Each of the seven sandpaper grades was placed on the Sheffield finger friction rig and the dynamic roughness procedure performed in the ungloved condition and when wearing the latex and nitrile examination gloves, using a single subject (no roughness magnitude estimation was required). The results are shown in Table 21.

7.3.2. Experimental design

Since the number of participants recruited in Buckley-Johnstone's [171] testing was too small to make a reasonable assessment of the viability of roughness discrimination for medical glove evaluation, further testing was conducted by the author at BM Polyco Ltd., using the same apparatus and procedure.

Ethical approval. Approval for the research was obtained from the University of Sheffield Research Ethics Committee (REC).

Participants. Test subjects were recruited from staff at BM Polyco Ltd. 21 people volunteered to participate. None had any known sensorimotor deficiencies or other major health problems. 12 performed the static test and 9 performed the dynamic test.

Gloves. As with Test Battery 2, Finex PF latex and Finite P Indigo AF nitrile examination gloves were used. The within-subjects factor in the test was hand condition, consisting of three levels: 'No Gloves', 'Best-Fit Latex' and 'Best-Fit Nitrile'.

Glove selection. The subjects were allowed to choose the size of glove that fitted them best for each type, with some help from the researcher. Most had some experience of using examination gloves through previous testing carried out at the company.

7.3.3. Roughness measurement

The FEPA grit designation is based on particle size. However, there are other factors that may influence the perception of 'roughness', such as the particle spacing and shape. Another way of quantifying the roughness of a surface is the roughness average (Ra), which expresses the arithmetic average of absolute values of height along a two-dimensional profile. A profilometer (Surftest SJ-400, Mitutoyo) was used to measure the Ra value of the sandpaper. Five samples were taken from each grade. A 12.5mm profile was measured on each sample and split into five equal evaluation lengths. The roughness average was calculated for each evaluation length and the mean of the 25 measurements taken as the Ra value for each grade.

The measured profiles were also processed using a MATLAB script that identified the peaks (Appendix D – described further in Section 7.8.4), The results are shown in Table 21.

7.3.4. Data analysis

Because each candidate used their own scale to quantify the roughness, and the ratings were based on relative magnitude, the arithmetic mean was not an appropriate measure, as it skews the results towards subjects who gave larger values and greater magnitude differences. Stevens [173] described a method. adapted in [172], that normalises and combines the results for all subjects as follows:

- Calculate the multiplier for each subject by dividing the grand mean of all magnitude estimations by the mean of the individual subject's magnitude estimations
- Multiply each subject's magnitude estimations by their individual multiplier
- Calculate the geometric mean for each sandpaper grade in each hand condition, where the geometric mean of n estimations is given by

$$Geometric\ mean = \sqrt[n]{x_1 . x_2 . x_3 \ldots x_n}$$

Although subjects were instructed to give a non-zero score for the perceived roughness, some subjects were unable to detect any roughness in some samples, particularly in the static tests in the gloved conditions, and so gave a score of zero. Since any datasets containing zeros will have a geometric mean of zero, the median was used instead in such cases, as recommended in [175].

7.3.5. Results

The data from the testing at BM Polyco Ltd. was combined with the data from Buckley-Johnstone's tests. The results of the objective measurements are shown in Table 21. Examples of the measured 2D profiles for each grade of sandpaper are shown in Appendix E.

Table 21. Geometric and friction measurements for roughness samples

FEPA Grit Designation	Ra (µm)	Average particle spacing (mm)	μ_d (No Gloves)	μ_d (Latex)	μ_d (Nitrile)
P40	62.9	1.47	1.21	1.40	0.92
P80	41.8	0.96	1.37	1.44	0.86
P120	25.5	0.56	1.13	1.26	0.78
P180	16.7	0.85	1.39	1.30	0.97
P240	15.8	0.39	1.29	1.30	1.01
P400	7.5	0.18	1.26	1.40	0.91
P800	4.4	0.18	1.20	1.24	0.85
		Mean	**1.26**	**1.33**	**0.90**

The coefficients of friction for each of the seven sandpaper grades with each hand condition are plotted against measured roughness average in Figure 64.

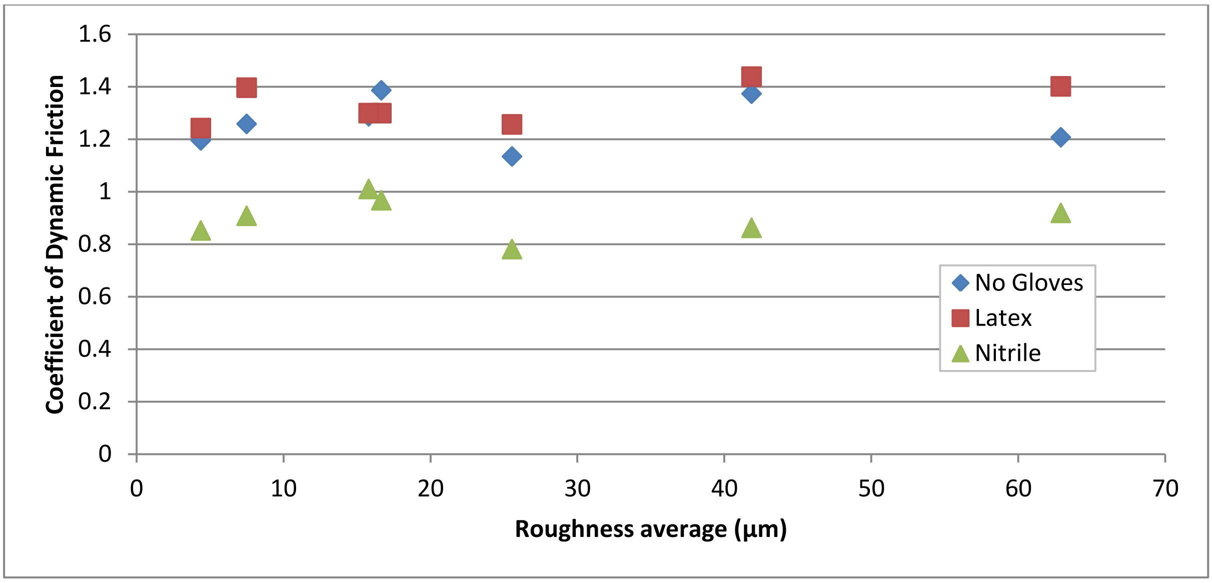


Figure 64. Dynamic coefficient of friction for roughness perception samples

The friction results for all three hand conditions were normal (p ≥ 0.297). Dynamic coefficient of friction for all three hand conditions was fairly constant across the range of sandpapers and does not correlate significantly with any of the three geometric measures (Pearson Correlations ≤ 0.585, p ≥0.168). However, the nitrile gloves showed a significantly lower coefficient of friction across the range than latex or bare hands. The results of the t-tests are shown in Table 22, and the schematic of significance is shown in Figure 65.

Table 22. Significance of differences in coefficient of friction

	Latex	Nitrile
No Gloves	NS (0.0091)	S (0.000)
Latex		S (0.000)

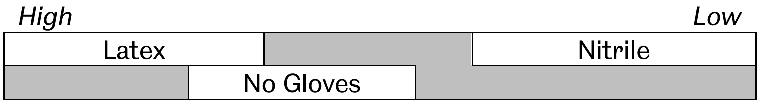


Figure 65. Schematic of significance for friction results

The relationship between the three geometric measures (Ra, particle diameter and average particle spacing) can be seen in Figure 66. There are strong and significant correlations between the three measures, as shown in Table 23.

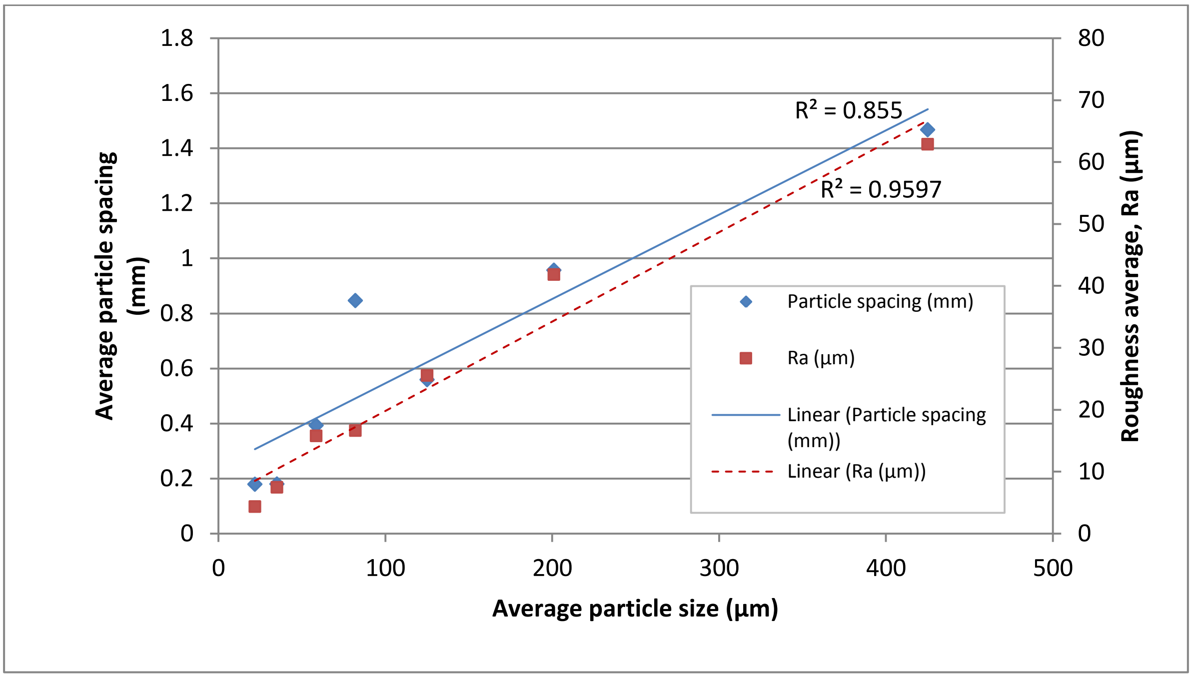


Figure 66. Correlations of the specified particle size to average particle spacing and roughness average

The particle spacing for the P180-grade sample is larger than expected. Inspection of shows that there is a much bigger variation of particle size and some larger particles that will increase the Ra although the particle spacing is large.

Table 23. Pearson correlations for roughness perception samples

		Particle Dia.	Particle Spacing
Ra	Pearson Correlation	0.980	0.934
	Sig. (2-tailed)	0.000	0.002
	N	7	7
Particle Dia.	Pearson Correlation		0.925
	Sig. (2-tailed)		0.003
	N		7

Dynamic Roughness Perception. There is a strong correlation between Ra and perceived roughness for all hand conditions, as can be seen in Table 24. Geometric mean perceived roughness is plotted against roughness average in Figure 67. It can be seen that the perceived roughness is highest in the ungloved condition for almost all values of roughness average. The perceived roughness is higher with latex gloves than nitrile at the rougher end of the scale. At the smoother end, the results merge together, as the roughness becomes too low to detect differences, even with bare hands.

The P180 grade shows a higher than expected perceived roughness, possibly because of the larger particle size, even though the particles are spaced further apart. It can be seen from Figure 68 that, when particle size is considered, the perceived roughness for the P180 (82μm) sample is closer to a linear trend with the values either side.

Table 24. Correlations between sandpaper geometry and geometric mean perceived roughness for each hand condition in the dynamic roughness perception test

		No Gloves	Latex	Nitrile
Ra	Pearson Correlation	0.989	0.995	0.994
	Sig. (2-tailed)	0.000	0.000	0.000
Particle Diameter	Pearson Correlation	0.960	0.989	0.987
	Sig. (2-tailed)	.001	.000	.000
Particle Spacing	Pearson Correlation	0.969	0.938	0.958
	Sig. (2-tailed)	.000	.002	.001

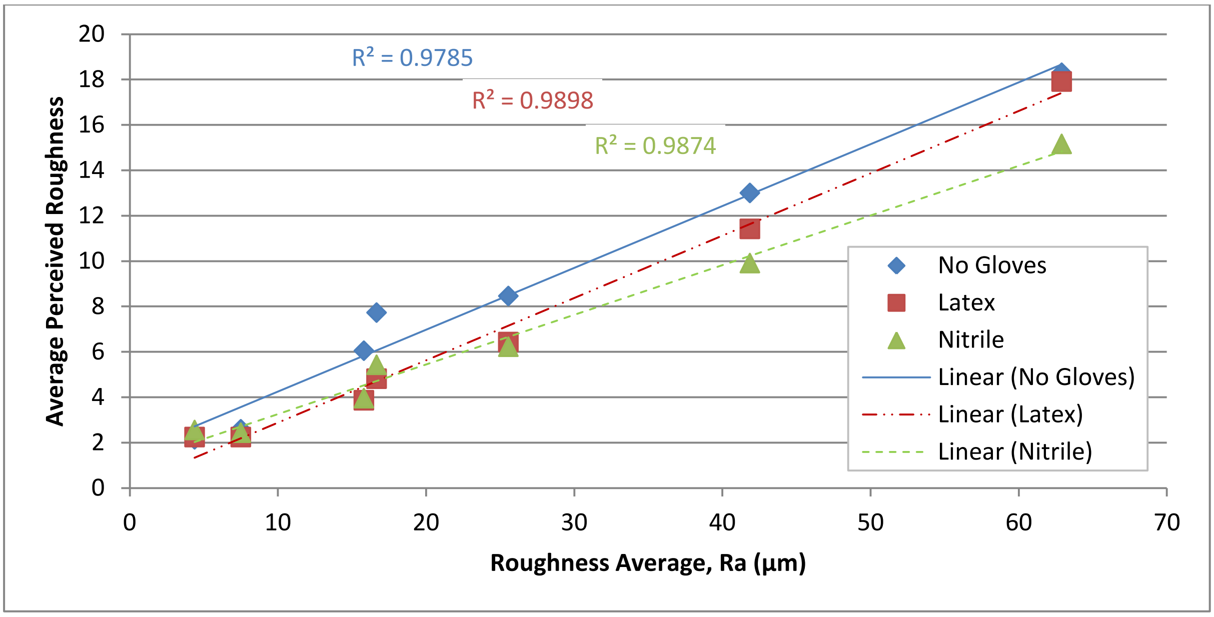


Figure 67. Average (geometric mean) perceived roughness in dynamic roughness perception testing of 16 subjects against roughness average (Ra) of sample

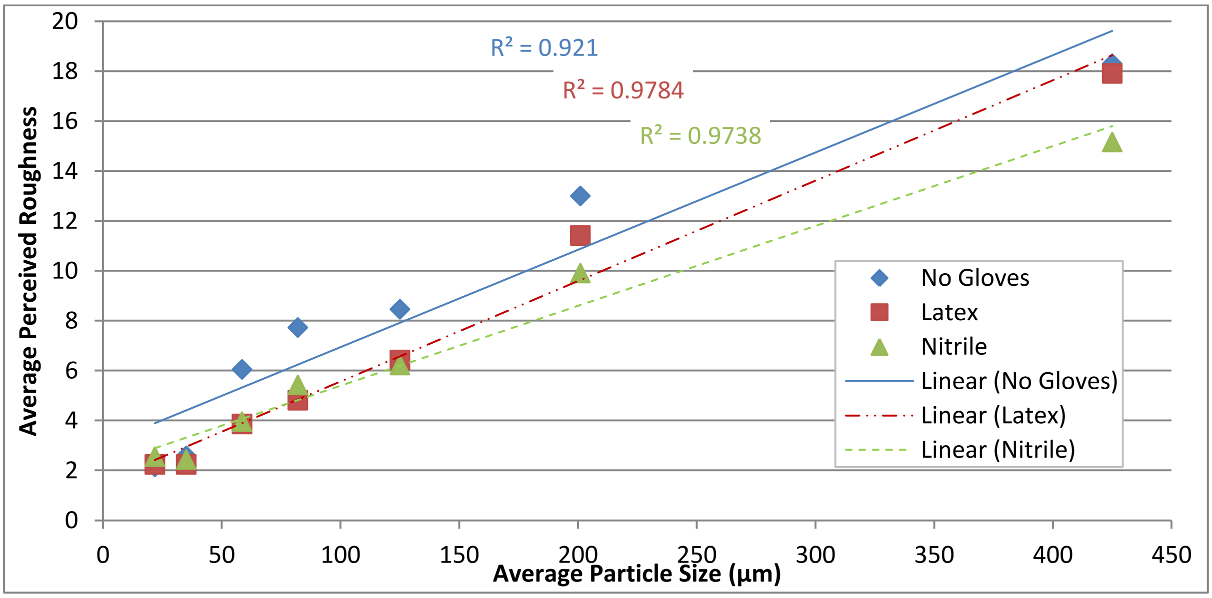


Figure 68. Average (geometric mean) perceived roughness in dynamic roughness perception testing of 16 subjects against particle size of sample

No significant deviation from normality was found in the dynamic roughness results ($p \geq 0.095$). Repeated-measures ANOVA using the geometric means from each of the seven grades showed significance for glove type ($p=0.007$). The results of paired t-tests are shown in Table 25, and a schematic of significance is shown in Figure 69.

Table 25. Results of paired t-tests between hand conditions in dynamic roughness perception testing

	Best Fit Latex	Best Fit Nitrile
No Gloves	S (0.021)	S (0.014)
Best Fit Latex		NS (0.353)

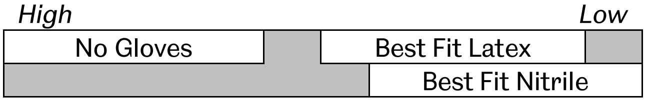


Figure 69. Significance of differences between hand conditions in dynamic roughness perception testing

Across the range of samples, perceived roughness was significantly higher in the ungloved condition, but the mean difference between the gloved conditions was not significant. When the paired differences in adjusted score between hand conditions were analysed for each candidate and grade (n = 16 x 7 = 112) using the Wilcoxon Signed Ranks Tests, the significance of differences between ungloved and gloved scores increased (p=0.000), but the difference between the latex and nitrile gloves was still not significant (p=0.758).

The results did not show a significant linear relationship between the dynamic coefficient of friction and the perceived roughness. The Pearson correlation was found to be 0.160 (p = 0.489).

Static Roughness Perception. The correlations between the three measures of geometry and the geometric mean perceived roughness for each sandpaper grade are shown in Table 26. The strongest correlations are found between particle diameter and perceived roughness. The relationship is shown in Figure 70.

Table 26. Correlations between sandpaper geometry and geometric mean perceived roughness for each hand condition in the static roughness perception test

		No Gloves	Latex	Nitrile
Ra	Pearson Correlation	0.960	0.865	0.910
	Sig. (2-tailed)	0.001	0.012	0.004
Particle Diameter	Pearson Correlation	0.984	0.945	0.973
	Sig. (2-tailed)	0.000	0.001	0.000
Particle Spacing	Pearson Correlation	0.895	0.828	0.882
	Sig. (2-tailed)	0.007	0.021	0.009

It can be seen that at larger particle sizes, the ungloved condition produced the highest perceived roughness values, while the latex again produced higher roughness values than nitrile. At the smoother end, there is little change in perceived roughness with particle size, and little difference between hand conditions.

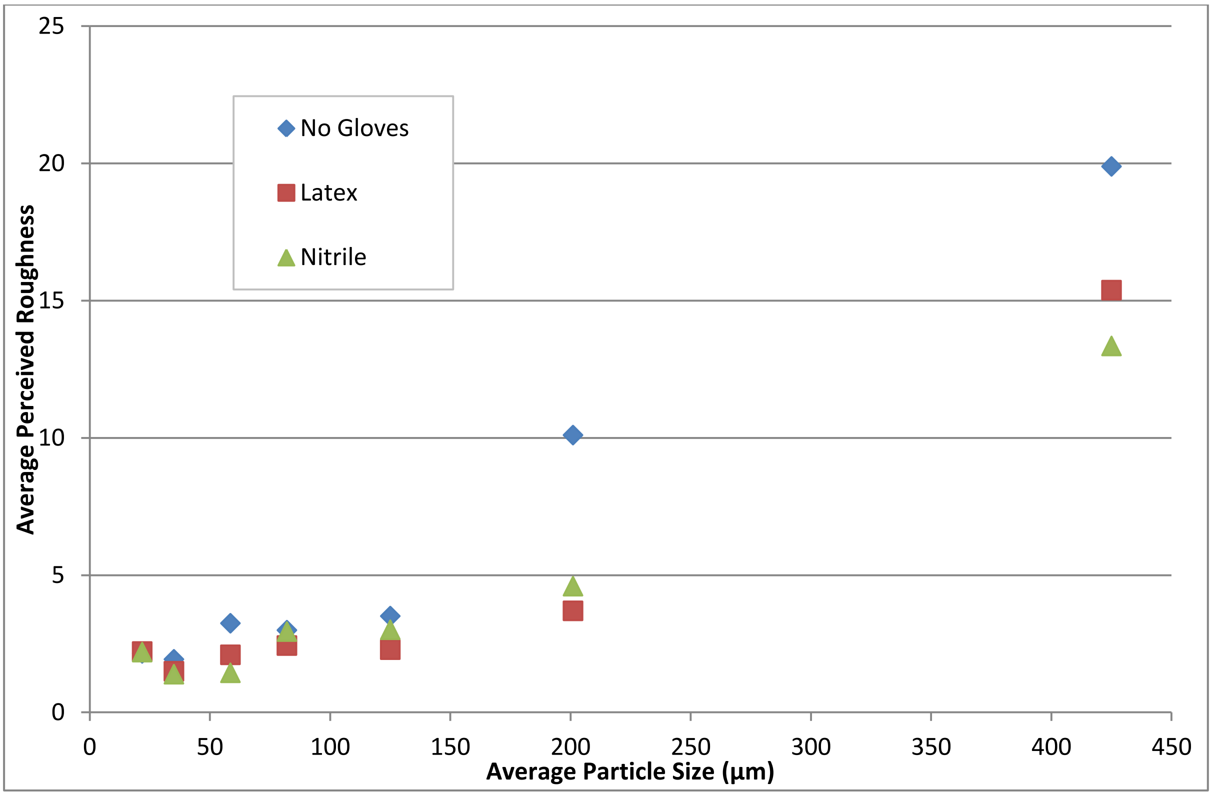


Figure 70. Average (geometric mean) perceived roughness in static roughness perception testing of 14 subjects against average particle size of sample

The distribution of the results deviated significantly from normality ($p \leq 0.005$), so the Friedman test was used to measure significance. It showed that hand condition did not have a significant effect on perceived roughness ($p = 0.066$). Since the *p* value was only just above the significance level, paired difference tests between the hand conditions were carried out. The results are shown in Table 27.

Table 27. Results of paired (Wilcoxon Signed Ranks) tests between hand conditions in static roughness perception testing

	Latex	Nitrile
No Gloves	S (0.028)	S (0.028)
Latex		NS (1.000)

When the paired differences in adjusted score between hand conditions were analysed for each candidate and grade (n = 14 x 7 = 98) using the Wilcoxon Signed Ranks Test, the significance of the differences between the ungloved condition and the gloved conditions increased (p = 0.000), but the difference between the gloved conditions was still not significant (p=0.608).

The results did not show a significant linear relationship between the dynamic coefficient of friction and the perceived roughness. The Pearson correlation was found to be 0.110 (p = 0.635).

7.3.6. Discussion

The dynamic tests showed more significant differences between hand conditions and more normal distributions than the static tests, but neither test was able to find any significant difference between latex and nitrile examination gloves in their effect on roughness perception.

Although the coefficient of friction was significantly lower with nitrile gloves than latex, friction was not found to correlate with perceived roughness in either the static or the dynamic test.

The biggest difference between the two tests appears to be their ability to discriminate between the smoother grades of sandpaper. While the dynamic test showed a fairly linear relationship between perceived and measured roughness, in the static test there was little difference between the average perceived roughness values for the five smoothest grades, all of which were very low in comparison to the values recorded for the rougher grades (less than 20% of the 'No Gloves' average for the roughest grade) and showed no increasing trend with particle size.

Hollins and Bensmaïa [176] examined the coding of roughness and provided a possible explanation for the difference in results between the two tests. They asserted that there were two physiological mechanisms or "codes" by which we perceive roughness. "Textures with spatial periods exceeding about 200 μm are encoded spatially," by SA I afferents while "perception of the roughness of finer surfaces is mediated by detection, primarily by Pacinian afferents, of cutaneous vibrations generated when textures move across the skin". So smoother surfaces cannot be distinguished by deformation-fired mechanoreceptors; they require movement to generate vibratory signals.

The particle spacing or "spatial period" at which the perceived roughness started to increase in the static test was 800 μm in all hand conditions (see Figure 71), which is larger than Hollins and Bensmaïa's value, but the particle spacing measurement may not have been accurate, and the two-phase nature of the graph supports the theory that there is a threshold spacing below which vibratory signals are essential to roughness perception.

Gloves had a significant effect on both test results, so it is difficult to analyse which of the codes is most inhibited by wearing gloves. Further tests in this chapter may yield more information. In terms of the usefulness of the tests in glove comparisons, neither a static nor a dynamic approach produced significant differences between the gloves. The dynamic test has the advantage of not producing zero-value responses, assuming that the method of magnitude estimation has been correctly explained and fully understood. Since the largest differences occurred with rougher surfaces, increasing the particle spacing and diameter across the range might yield better results. The 'Bumps' test detailed in Section 7.5 test tactility in a similar way, but on a larger scale.

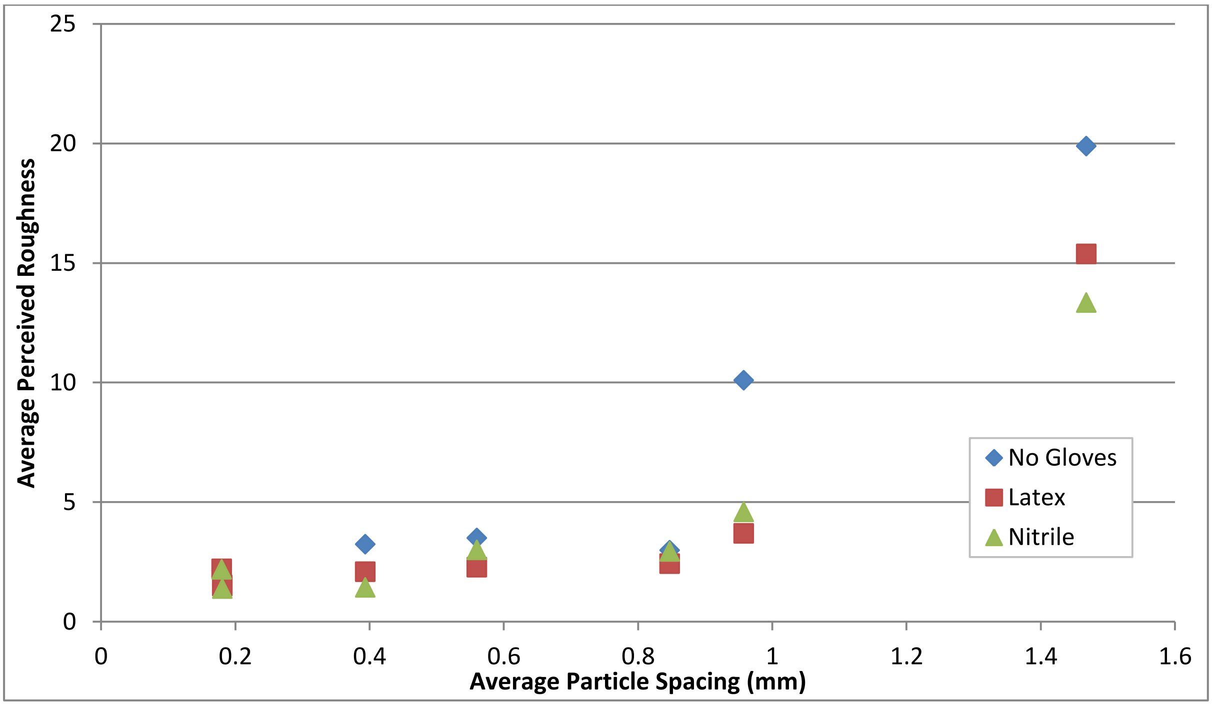


Figure 71. Relationship between perceived roughness and average particle spacing for static tests

7.4. Simulated Medical Examination Tactility Test (SMETT)

7.4.1. Background

Examinations performed by medics can include feeling for surface irregularities, such as thyroid nodules, and feeling changes in stiffness under the surface, such as in a breast examination. Gnaneswaran et al. [53] designed a test intended to simulate ‘feeling the human skin for diagnosis’, which is discussed in Chapter 3 (see Figure A 28).

It was decided to further develop this idea to include detection of changes in both geometry and stiffness. There were three main issues identified with the original test:

- a lack of randomisation which led to significant learning (the subjects knew where to expect the bumps);
- the coarseness of the original bumps (approximately 13 mm diameter), which made them very easy to detect;
- a lack of resolution in the tests – since the bumps were all the same size, it was likely that they would either all be detected, or none.

It was proposed to overcome these issues by:

- separating the foam into discrete blocks, some of which contain bumps, others of which do not – this allows the blocks to be rearranged to create randomisation;
- producing bumps of five different sizes, so that a threshold size can be determined for a given hand condition;
- reducing the size of the bumps.

7.4.2. Prototype Mark I

Two versions of the ‘Bumps’ test were produced. The first used liquid latex applied onto upholstery foam in different sized droplets. The second consisted of hot-melt adhesive applied to the foam, and covered by a layer of silicone (see Figure 72). This allowed some assessment of the effect of lump stiffness and the effect of having a consistent texture (with the silicone) as opposed to varying it (with the latex bumps on foam). The bumps were produced in five discrete sizes, giving five levels of difficulty for the test, with the smallest bumps being the highest difficulty.

In order to simulate detection of hard lumps under the surface, a test was also developed on the 'Princess and the Pea' principle. A hard bead of approximately 10mm diameter was suspended in a block of foam, and layers of foam sheet were placed on top of it. The number of layers was varied to give five levels of difficulty, with the most layers being the highest difficulty. In order to ensure that the surface was level, the same total number of foam sheets was used in each block, but the number above the bead was varied (see Figure 73).

A photograph of the prototype can be seen in Figure 72.

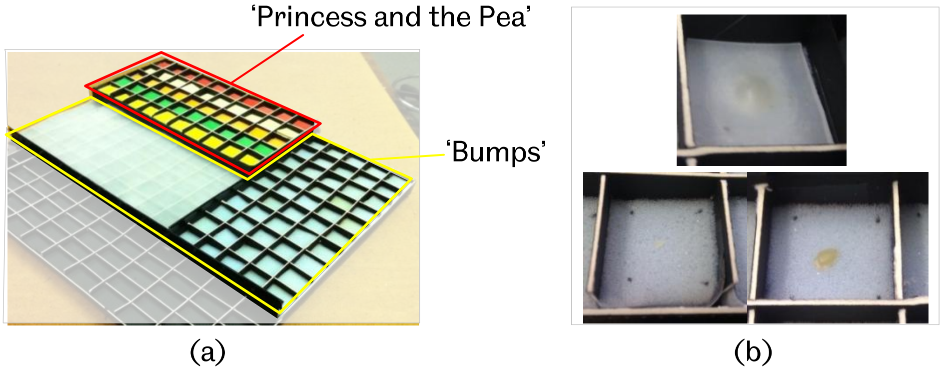


Figure 72. Simulated Medical Examination Tactility Test (SMETT) prototype Mk I (a) overview and (b) close-up of 'Bumps' modules

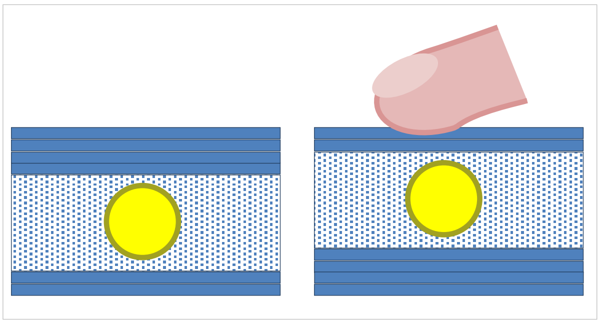


Figure 73. Schematic of SMETT prototype

The prototype was tested on two participants in five different hand conditions, varying in glove material, thickness and fit. All of the gloves used were PolycoHEALTHCARE powder-free examination gloves. The results are shown in Figures 74-76.

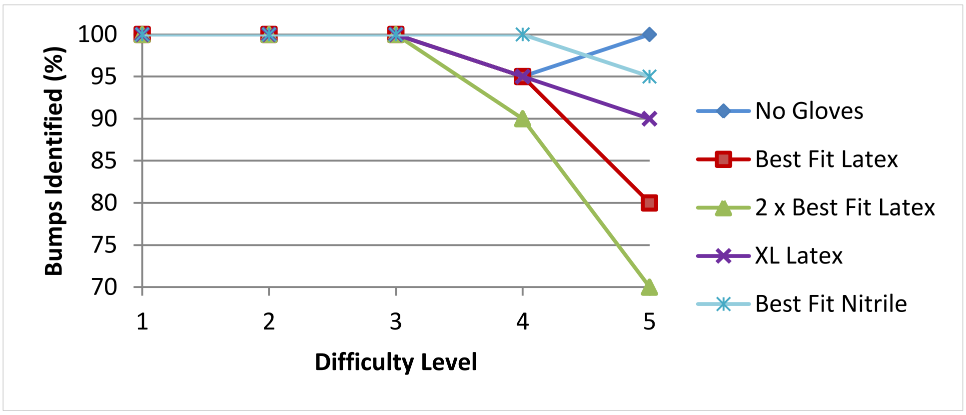


Figure 74. SMETT 'Latex bumps' preliminary results

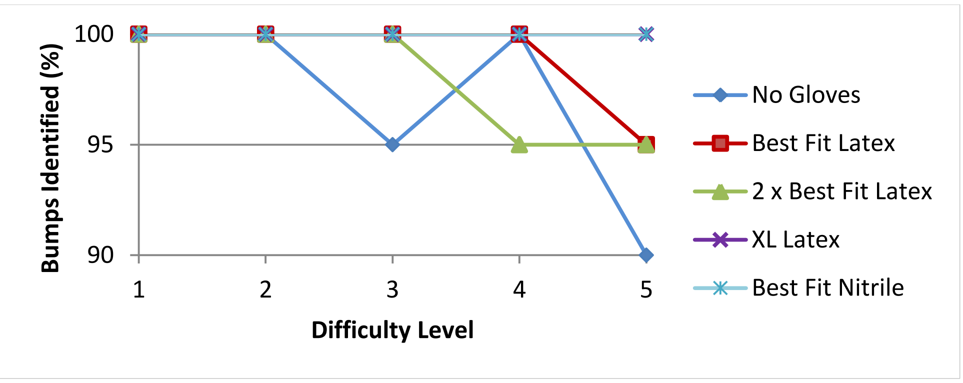


Figure 75. SMETT 'Glue bumps under silicone' preliminary results

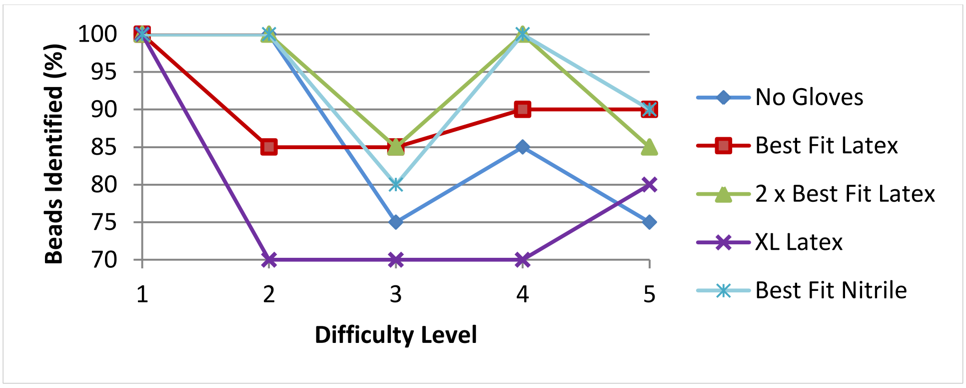


Figure 76. SMETT ‘Princess and the Pea’ preliminary results

Of the three tests, the latex bumps show the most promise, with some difference between the results for the hand conditions. As expected, the larger bumps (the lowest difficulty level) could be detected with all hand conditions, and performance generally dropped off as the bump size decreased. The ‘No Gloves’ condition and the nitrile gloves performed best, with two layers of latex gloves performing worst. There is less discrimination with the ‘Glue bumps under silicone’, but the same pattern of performance decrease with increasing bump size emerges. The results for the ‘Princess and the Pea’ (P&P) test are less clear, although the extra-large gloved condition clearly performed worst.

The results showed enough promise for the test to be worth developing. However, further issues identified with the test were:

- Difficulty in producing bumps of consistent size and shape
- Most of the bumps were too large and easily detectable even with multiple layers of examination gloves on
- Randomisation of the bump location was a lengthy process
- It was felt that mixing up the bump sizes would make a more realistic test and reduce learning
- There were issues with durability, particularly with the ‘Princess and the Pea’ test, which quickly became damaged when participants applied excessive force. The latex bumps also become detached from the foam.

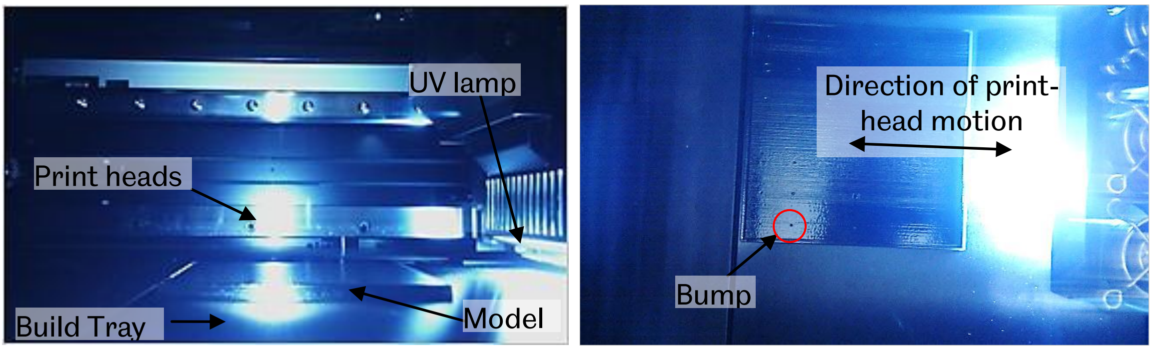
7.5. SMETT ‘Bumps’ Test

7.5.1. Rapid prototyping

It was decided to attempt to produce the ‘Bumps’ test using rapid prototyping. This would allow for smaller and more consistent bump sizes and more durability. A tester sheet was manufactured on the ZCorp 510 printer, which constructs the model by spreading a layer of powder and selectively depositing a binding material. The model was created in SolidWorks, and consisted of a flat plate with raised hemispheres ranging from 50 µm to 500 µm radius. However, the printer failed to reproduce any of the raised bumps. The resolution of the powder was thought to be too large for the required geometry.

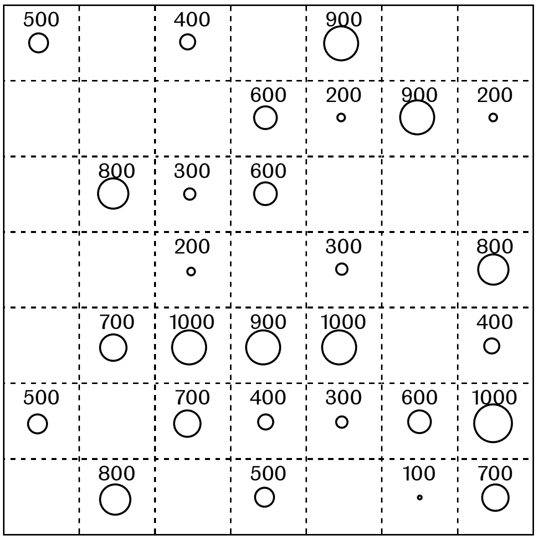
7.5.2. SMETT ‘Bumps’ Mark II

Following the ZCorp test, the University of Sheffield acquired an Objet Eden260V™ printer, which uses polymer jet technology to create models from polymer resin, in a similar way to an inkjet printer, creating layers by selective deposition of droplets and curing each layer with a UV lamp to build up a 3D structure. The machine initially had a hard resin installed, so a prototype was made using this material, with a similar SolidWorks model to the one used for the ZCorp test. However, it was too easy to feel the lumps, and the material was considered to be too dissimilar to human tissue. A softer rubber (TangoBlackPlus™) was used to create a prototype in which the bump size and location was varied so as to appear random to test participants. The CAD model consisted of a 140 x 140 x 5 mm flat plate from which 28 raised hemispheres of diameter 100µm-1mm protruded in a 7x7 formation (21 of the locations were blank). The printing process can be seen in Figure 77 and a schematic of the bump sizes locations can be seen in Figure 78.



(a) (b)

Figure 77. 3D printing of the SMETT prototype in the Objet printer (a) side view and (b) top view



500		400		900		
			600	200	900	200
	800	300	600			
		200		300		800
	700	1000	900	1000		400
500		700	400	300	600	1000
	800		500		100	700

Figure 78. Schematic of bump sizes and locations for SMETT 'Bumps' Mk II (not to scale)

The resolution of the Objet printer, according to the manufacturer [177], is 600 dpi in the x- and y-axes, and 1600 dpi in the z-axis, which correspond to a layer thickness of 16μm and a droplet width of 40μm. Clearly this means that the printer is unlikely to reproduce exactly a hemisphere of 100μm diameter. The geometry of the prototype was measured using a microscope and a profilometer. The size of the bumps meant that the profilometer measurement varied significantly depending on where the profilometer path intersected the bump, so the results were disregarded. However, a comparison of the diameter as drawn in the CAD and as measured on the microscope is shown in Table 28.

Table 28. Comparison of CAD and measured geometry on SMETT Mk 2

CAD diameter (µm)	Quantity	Mean measured diameter (µm)
100	1	277
200	3	385±7
300	3	513±7
400	3	605±32
500	3	680±10
600	3	793±34
700	3	906±20
800	3	1006±21
900	3	1080±14
1000	3	1192±2
Total	28	

All of the bumps are larger in diameter than designed, even at 1 mm diameter, possibly due to the spreading of the polymer droplet before it has been cured by the UV lamps. However, there is good separation between the sizes of bumps.

7.5.3. Calibration and refinement (testing required lump sizes)

The range of diameters was chosen fairly arbitrarily. In order to determine what range of diameters produce measurable differences in performance between gloves, preliminary testing of the Mk II test was carried out with 9 participants using the same five hand conditions as in Test Battery 1, with the order randomised to counter any learning effects.

Procedure. It was found that the coefficient of friction of the rubber, particularly with skin, was very high, and the vibrations made identification of the bumps difficult. In order to reduce the friction, talcum powder was sprinkled onto the surface, spread around and any loose particles brushed off. The subject was shown the test rig and told that there were bumps of different sizes on the surface which they would be asked to identify. They were then blindfolded and the orientation of the rig was randomised (an ‘x’ was drawn in one corner to assist the researcher in setting the orientation). They were asked to explore the surface of the rubber by drawing the index finger of their dominant hand across the surface in rows or columns and to indicate if they felt any ‘bumps’. A card guide was used to keep the fingertip in one row or column at a time. The subject was allowed to explore the area at their own pace and to go back and forwards until they were sure about how many bumps they could identify in that row or column. The researcher had a schematic of the test area and marked those bumps that were identified. The test was then repeated with each hand condition, with a different orientation, and with the talcum powder being reapplied when necessary.

Results. The mean percentage of bumps identified at each nominal diameter is shown in Figure 79.

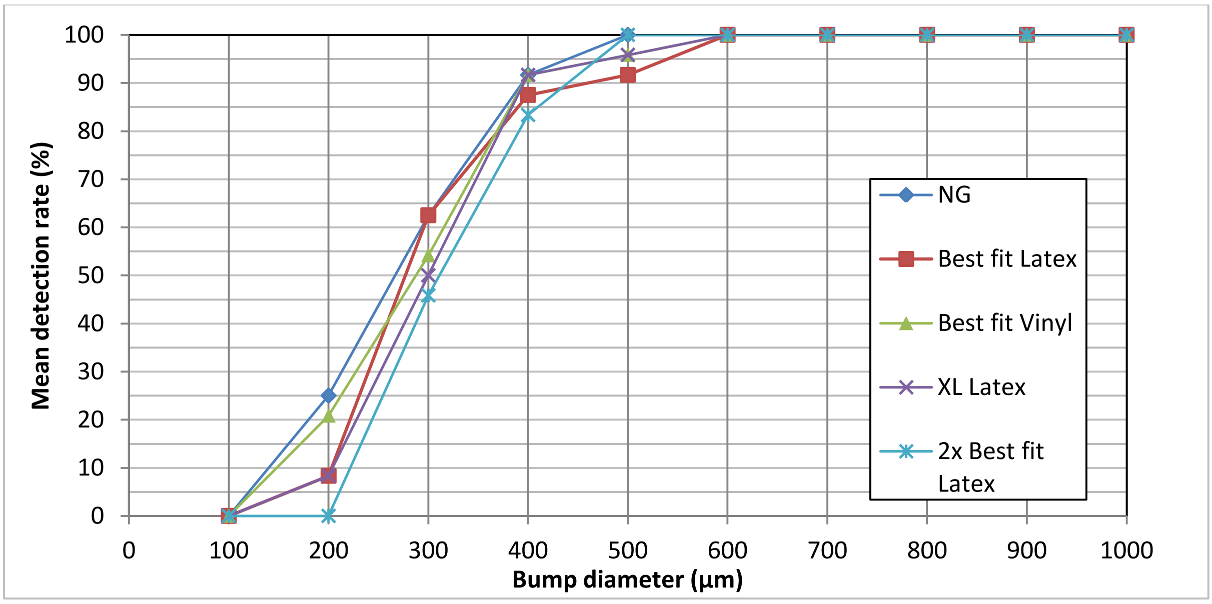
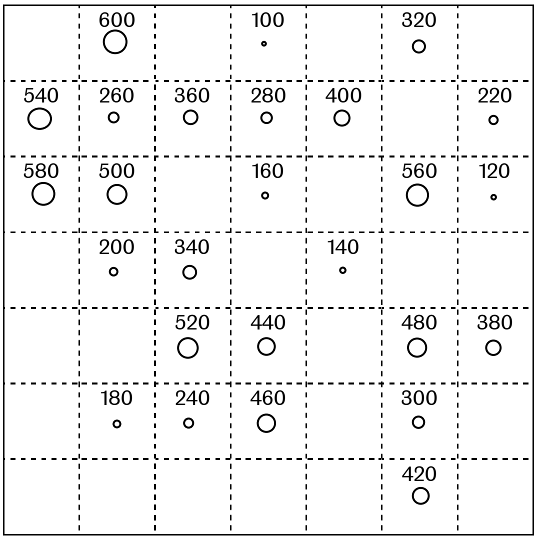


Figure 79. Preliminary testing of SMETT ‘Bumps’ (lines displayed for clarity only)

The results showed some differences in performance between hand conditions in the 200µm to 600µm range. At larger diameters, all the bumps were detected in all conditions (even with two layers of gloves) and at 100µm no detections were made in any condition. The ‘No Gloves’ (NG) condition appeared to give the best performance, while the double layer of latex gloves performed worst, which follows the trend found in the other tactility tests.

7.5.4. Final design – SMETT ‘Bumps’ Mk III

In order to produce more significant differences in performance between glove conditions, the test rig was redesigned to focus on the 100-600µm diameter range where the detection rate was non-zero, but less than 100%. The number of bumps was reduced from 28 to 26, so that the diameters were spaced equally between 100 and 600 micrometres in increments of 20 micrometres. A schematic is shown in Figure 81.



	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 80. Schematic of nominal bump sizes and locations for SMETT 'Bumps' Mk III (not to scale)

The diameters were again measured using a microscope, and the deviation of the average diameter from the CAD model is shown in Figure 81 for both the Mark II and the Mark III prototypes.

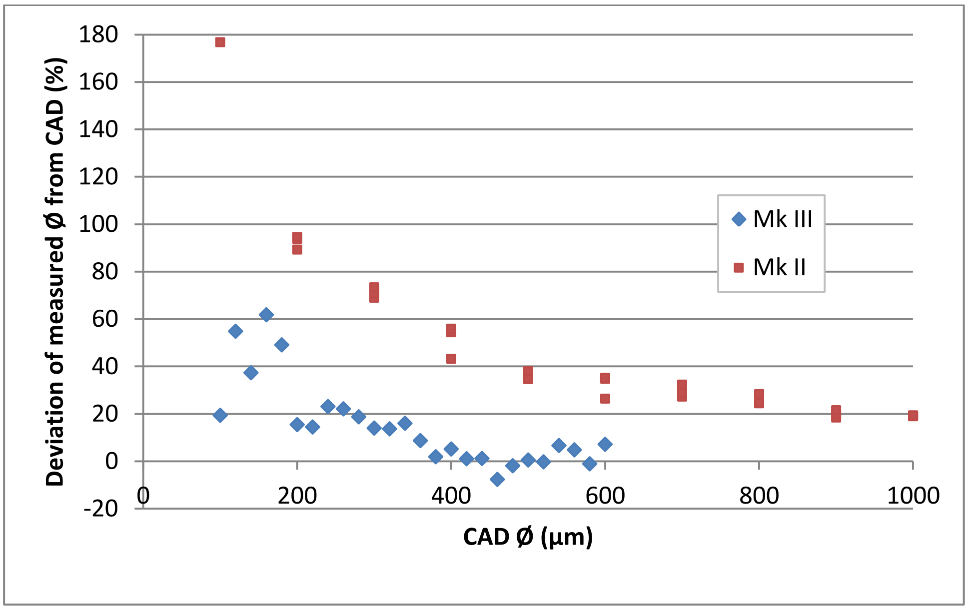
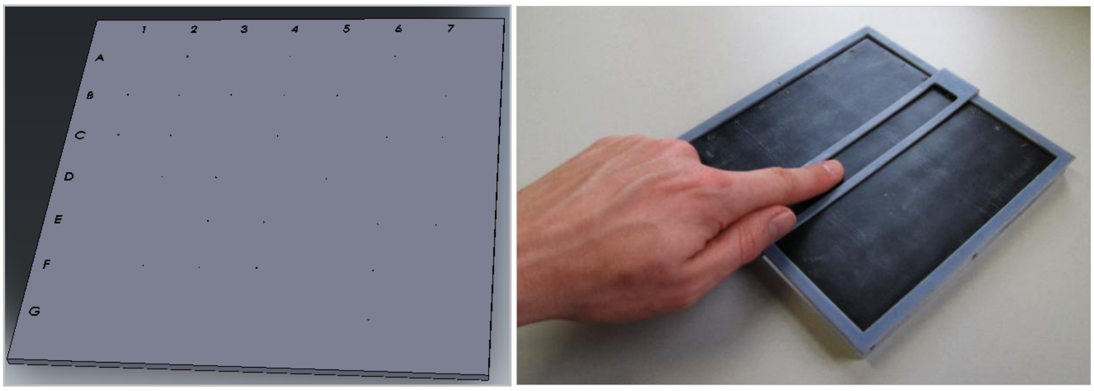


Figure 81. Manufacturing errors in 3D printing of 'Bumps' prototypes

It can be seen that although the manufactured dimensions exceed those specified in the CAD model, the deviation is much smaller than in the previous prototype, perhaps due to cleaner print heads. Unsurprisingly the deviation is much larger at small diameters, but does not exceed 62% in the Mark III.

The design of the prototype was adjusted to include a recessed reference grid (A-G and 1-7), and the guide was produced from VeroBlue™, a hard plastic. It comprised a frame and sliding rail. This was found to warp too easily, and so was redesigned after a number of tests, and a thermoplastic base was added. The final design can be seen in Figure 82. The sliding rail can be removed and turned 90°, and includes notches that mate with grooves on the frame to locate the rail in a row or column.



(a) (b)

Figure 82. SMETT ‘Bumps’ Mk III (a) CAD model and (b) finished test

7.5.5. Experimental design

Ethical approval. All the tests protocols, along with participant information sheets and consent forms, were submitted to the University of Sheffield Research Ethics Committee (REC) and received approval.

Participants. Test subjects were recruited from a first year mechanical engineering course. 34 students volunteered to participate. None had any known sensorimotor deficiencies or other major health problems.

Gloves. As with Test Battery 2, Finex PF latex and Finite P Indigo AF nitrile examination gloves were used. The within-subjects factor in the test was hand condition, consisting of three levels: ‘No Gloves’, ‘Best-Fit Latex’ and ‘Best-Fit Nitrile’.

Glove selection. The subjects were allowed to choose the size of glove that fitted them best for each type, with some help from the researcher.

Procedure. The test procedure was unchanged from the Mark II testing. The order of the hand conditions was randomised.

7.5.6.Results

The results are shown in Figure 83, separated into mean detection rates for each size of bump. The results of two subjects were excluded due to significant abnormalities in the results in all hand conditions (a number of non-detections of large bumps despite detections of much smaller ones). The abnormalities may have been due to insufficient lubrication with talcum powder. It can be seen that bumps start to be detected above 140 micrometres, and at 320 micrometres, the bump was detected by all subjects in two of the three hand conditions. Significant differences appear to exist between the treatments for some bumps in this range.

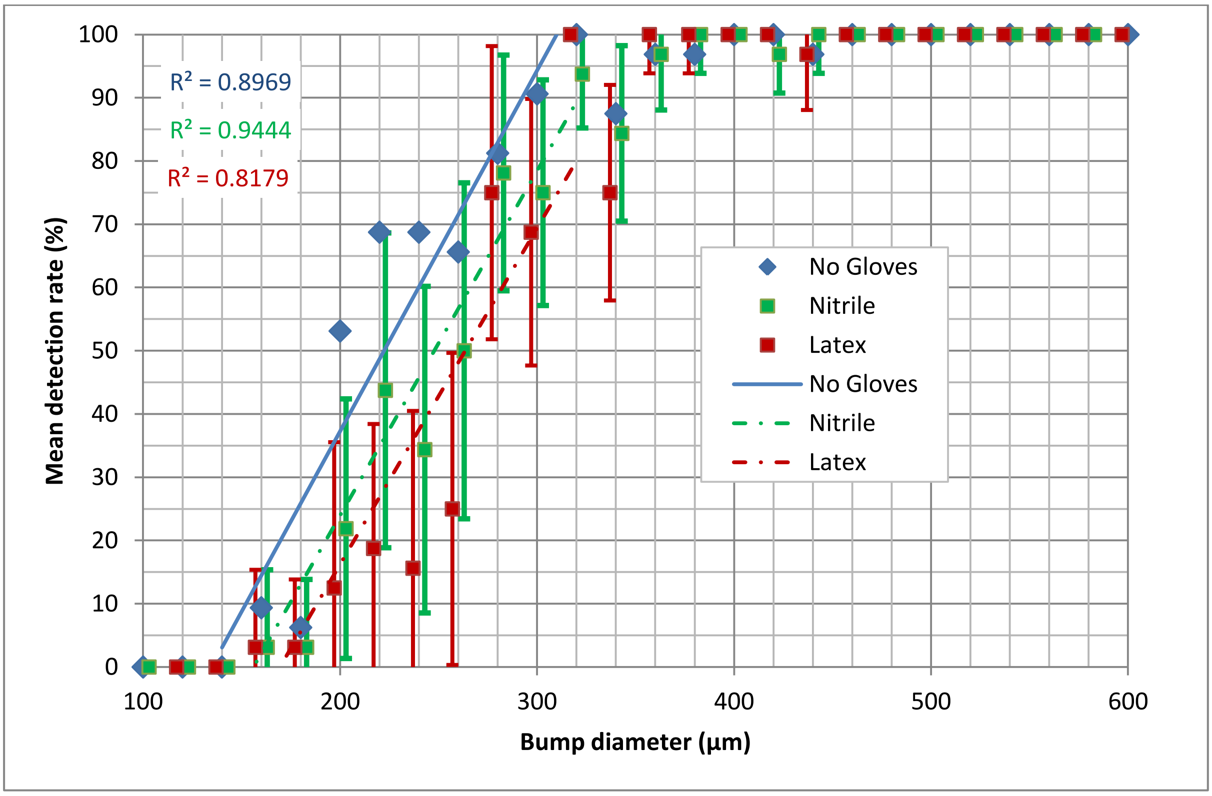


Figure 83. Mean detection rates per bump for 32 subjects wearing nitrile and latex gloves and ungloved (with 95% confidence intervals of the difference to the ungloved condition; treatments separated horizontally for clarity)

The mean detection rates for the whole range of bumps and in the range 140-320µm are shown in Figure 84. The highest mean detection rate was achieved in the ungloved condition, while subjects scored lower on average with latex gloves than with nitrile.

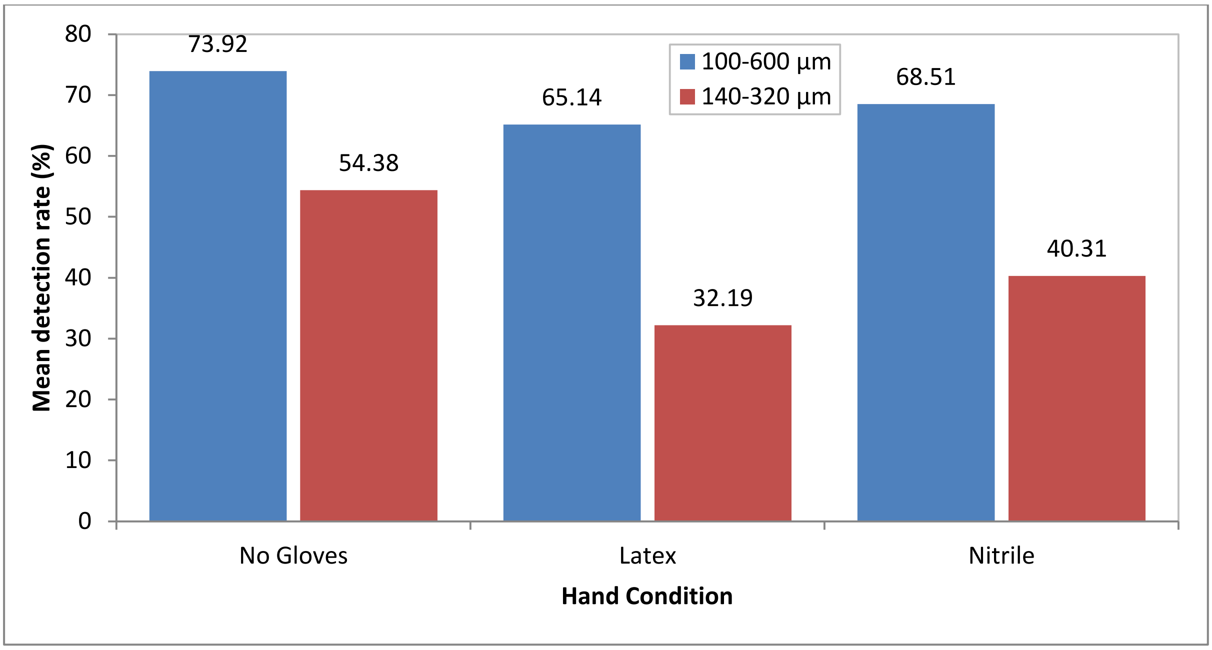


Figure 84. Results of the SMETT 'Bumps' Mk III testing, showing mean detection rates across the full range of bumps and in the range 140-320µm (n=32)

Figure 85 shows the mean differences in performance of the two gloved conditions to the bare-handed condition, expressed as a percentage of the mean ungloved performance.

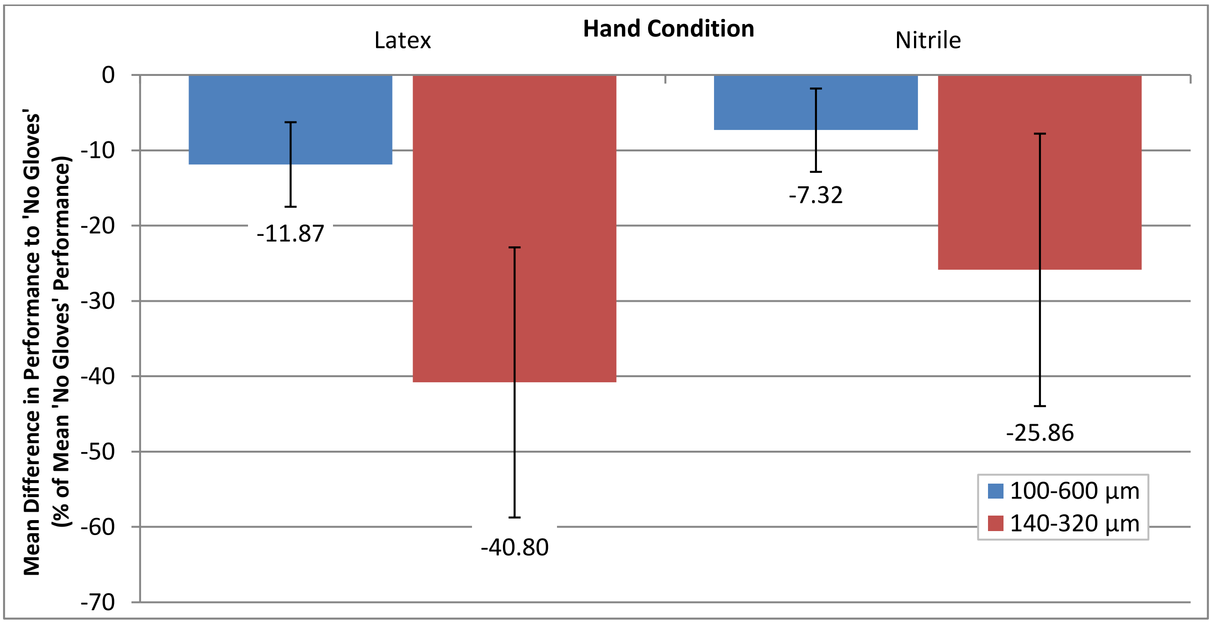


Figure 85. Mean difference in performance (detection rate) to the ungloved condition of subjects wearing latex and nitrile examination gloves in the SMETT 'Bumps' Mk III test as a percentage of mean ungloved performance, showing results

across the full range of bumps and in the range 140-320μm (with 95% confidence intervals)

Even taking all bumps into account, subjects scored significantly less in the gloved conditions than in the ungloved condition. The differences are more pronounced when narrowing the range, but the gloved conditions do not appear to show significant differences.

Statistical analysis. Two of the treatments for the full range and all three for the 140-320μm range showed significant non-normality in the Shapiro-Wilk test, so the Friedman test was used to analyse the significance of the differences. In both ranges, hand condition was a significant factor in detection rate (p=0.000). The results of the Wilcoxon Signed Ranks tests for pairs of treatments are shown in Tables 29 and 30 for the full range and the narrowed range respectively. Schematics of the differences (significance being signified by horizontal separation) are shown in Figures 86 and 87.

Table 29. Significance of paired differences for SMETT 'Bumps' Mk III (100-600 μm)

	Latex	Nitrile
No Gloves	S (0.001)	S (0.017)
Latex		NS (0.080)

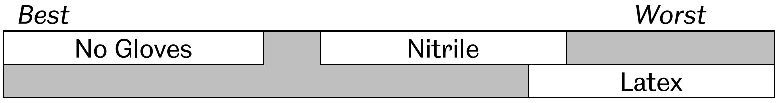


Figure 86. Schematic of differences between treatments for SMETT 'Bumps' Mk III (100-600 μm)

Table 30. Significance of paired differences for SMETT 'Bumps' Mk III (140-320 μm)

	Latex	Nitrile
No Gloves	S (0.001)	S (0.010)
Latex		NS (0.065)

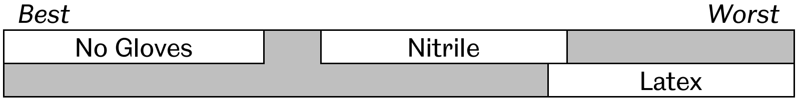


Figure 87. Schematic of differences between treatments for SMETT 'Bumps' Mk III (140-320 μm)

It can be seen that, as predicted, there are no statistically significant differences in performance between the latex and nitrile gloves, but the difference is more pronounced (p=0.065) when the smaller and larger bumps are ignored.

7.5.7. Further investigations and refinement of the test

During the testing, a number of possible issues with the testing procedure and the design of the rig emerged. It can be seen from Figure 88 that there are some unexpected dips in the detection rate across all treatments at certain diameters, particularly the 340μm diameter bump. It was also noted that some bumps (particularly 160, 180 and 240μm) were easier to detect in one orientation than other, which might suggest some non-sphericity in the bumps, and could affect the results given that orientation was varied between tests.

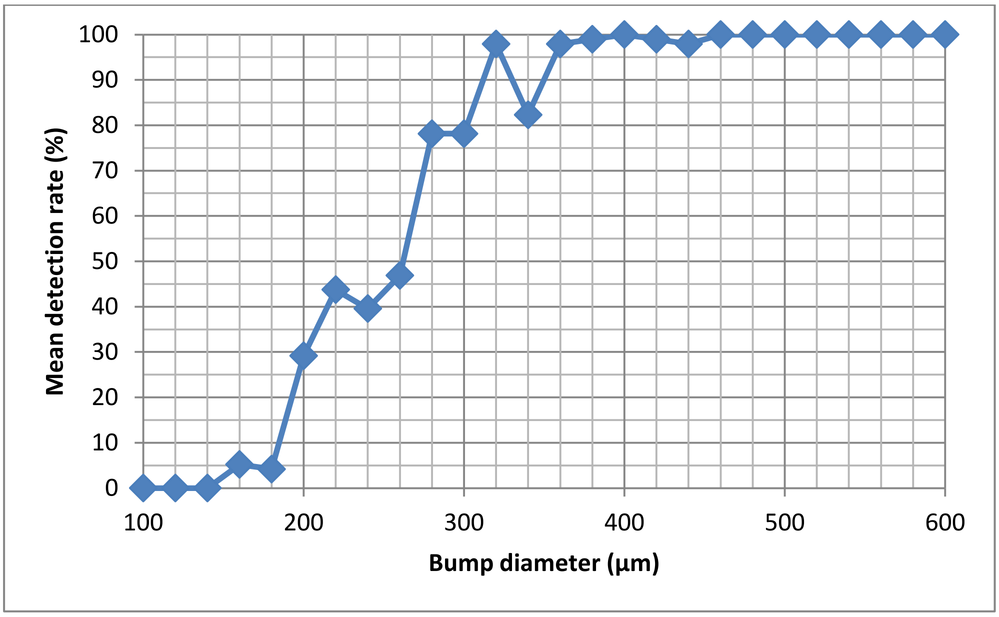


Figure 88. Mean detection rate in the SMETT 'Bumps' Mark III for all treatments

As discussed previously, the friction levels were very high when the rubber was not lubricated with talcum powder, and the level of lubrication could affect the detection rate. Finally, it was also noted during testing that technique varied between subjects in terms of angle of attack of the finger, with some placing the terminal *phalanx* flat on the surface, while others had it almost perpendicular to the surface with only their fingertip in contact with the rubber (see Figure 89).

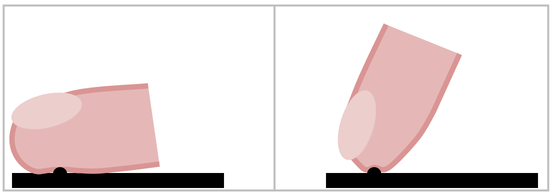

(a) (b)

Figure 89. Technique variations in the SMETT 'Bumps' test: (a) flat terminal phalanx; (b) perpendicular phalanx

This variation in technique could have a number of effects. As noted in Chapter 2, Johansson and Vallbo [14] found that the innervation density, particularly of the FA I and SA I afferents that detect edge contours and were more useful in identifying Braille [16], was much higher in the *distal* half of the terminal *phalanx* than in the *proximal* half. Because of the shape of the fingertip, holding the finger flat could also mean that bumps close to the frame were more likely to be missed as the fingertip would butt against the guide. The orientation of the test could also have a similar effect, with the end bumps on rows being more likely to be overlooked or obscured by the finger hitting the guide.

These issues were explored in a number of tests on an individual subject, who was not naïve to the test. All the tests were done bare-handed, since it was the apparatus and technique rather than the gloves that were being tested. Three variables (orientation, lubrication, and technique) were tested in 12 tests. The treatments for each test are shown in Table 31.

Table 31. Treatments in three variables for SMETT 'Bumps' testing

Test	Orientation (degrees)	Lubrication	Technique
1	0	None	Flat phalanx
2	180	None	Flat phalanx
3	90	None	Flat phalanx
4	270	None	Flat phalanx
5	0	Talcum powder	Flat phalanx
6	180	Talcum powder	Flat phalanx
7	90	Talcum powder	Flat phalanx
8	270	Talcum powder	Flat phalanx
9	0	Talcum powder	Fingertip
10	180	Talcum powder	Fingertip
11	90	Talcum powder	Fingertip
12	270	Talcum powder	Fingertip

Results. The mean detection rates for the four orientations across the twelve tests are shown in Figure 90.

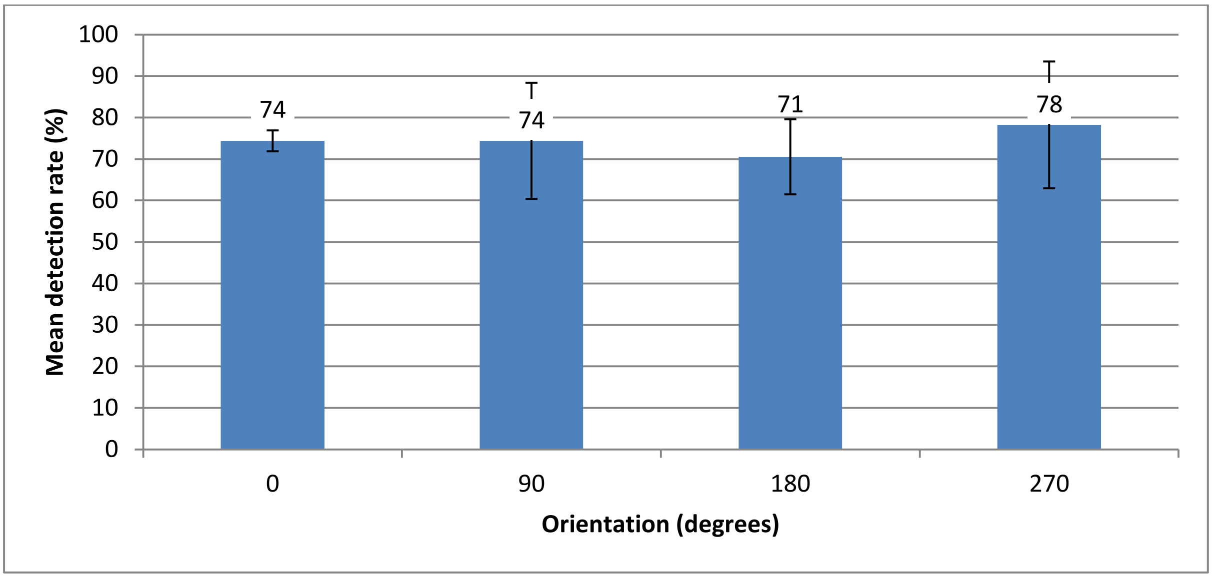


Figure 90. Results of varying the orientation for the SMETT 'Bumps' Mark III test (with 95% confidence intervals)

Orientation does not appear to have a significant effect on detection rate. The biggest differences in detection with orientation were found in the 200, 220 and 260μm bumps. Only one of these is on the edge of the grid, suggesting the problem is one of geometry. The microscope measurements showed significant non-circularity of the bump footprint, and lips could have been created on certain sides of the bumps by printing inaccuracy. The bumps may also wear down with repeated testing.

More detailed inspection of the geometry with a non-contact profilometer might yield a clearer explanation. For the purposes of the glove testing conducted, the randomisation of orientation of the test should also have reduced its impact.

The mean detection rates for the dry and powdered results (with flat *phalanx*) are shown in Figure 91.

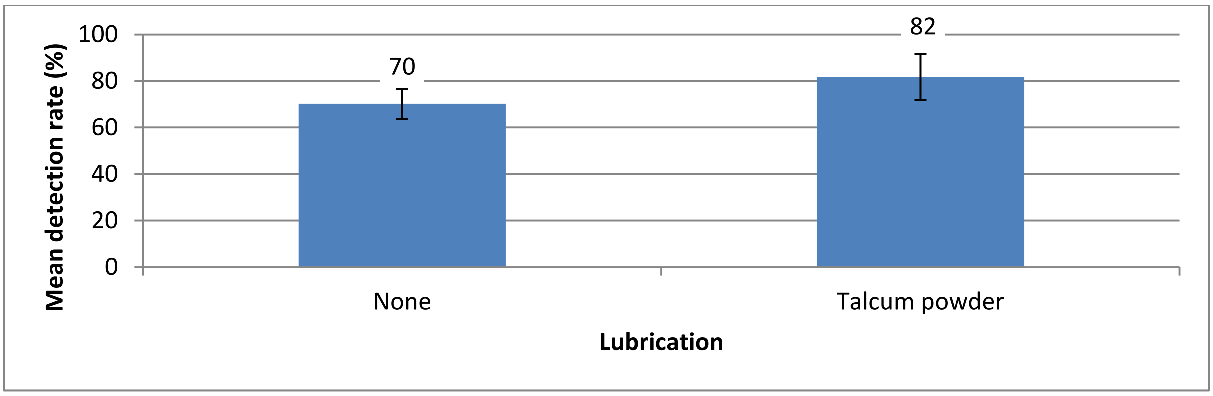


Figure 91. Effect of lubrication on SMETT 'Bumps' detection rate (with 95% confidence intervals)

The detection rate appears to be significantly higher with talcum powder than with a clean, dry surface. This is consistent with observations made in the testing that the level of vibration on a dry surface made detection of bumps difficult. Whether the exact level of lubrication is significant has not been established. Certainly, a more robust protocol for lubrication could be designed.

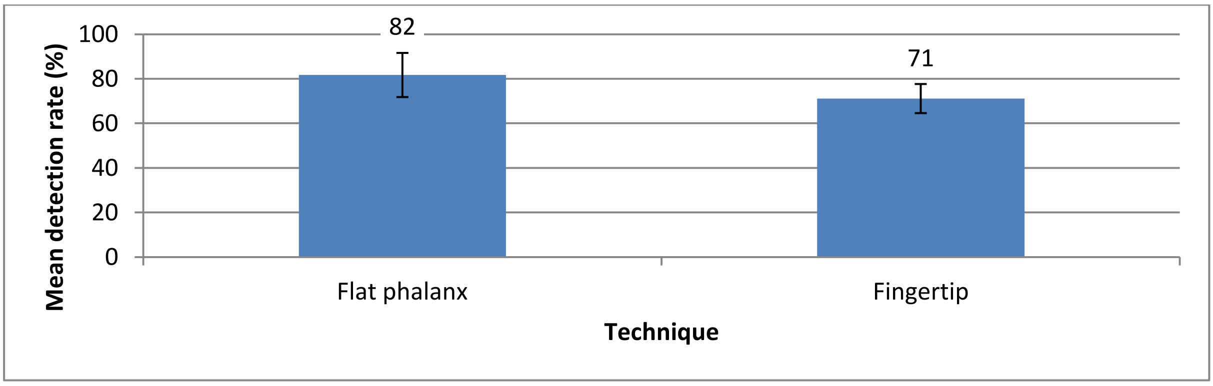


Figure 92. Effect of technique on SMETT 'Bumps' detection rate (with 95% confidence intervals)

The results of the lubricated tests with the terminal *phalanx* flat against the surface and approximately perpendicular to it are shown in Figure 92. The detection rate is significantly higher with the terminal *phalanx* flat against the surface than using the fingertip. This result is somewhat surprising, but the significant difference shows that there is a need to specify the technique used in order to ensure consistency. While subjects generally used the same technique across all hand conditions, specification of one technique will allow performance norms to be defined more clearly and so is recommended.

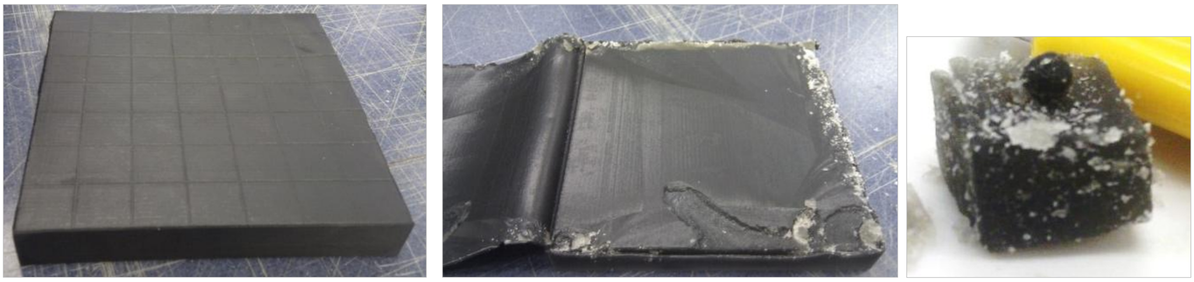
7.5.8.Discussion

The superior tactile performance achieved when ungloved is as expected, and matches the results in the other tactility tests. The nitrile glove performs better than the latex, although the *p* value, the probability of the means being equal, is slightly above the significance level of 0.050. Explanations for this will be explored in Chapter 12, but one possible explanation could be the glove thickness, with Indigo nitrile gloves having an average thickness of 74μm, and the Finex® latex gloves being 123μm thick on average (see Section 11.2). Thicker gloves could be expected to attenuate the tactile signal by deforming more when going over a bump, so that skin deformation is reduced.

7.6. SMETT ‘Princess and the Pea’ Test

7.6.1. Development

The Objet printer was used to produce a prototype ‘Princess and the Pea’ (P&P) test. The SolidWorks model consisted of a 140x140x20mm hollow box in which 27 spheres “floated” at different randomised heights. As with the ‘Bumps’ test, the location of the spheres was randomised within a 7x7 grid. The printer works by producing a support structure for overhanging features, consisting of a support jelly reinforced by a scaffold of model material. Since the CAD model included a top layer covering the whole model, the space inside the box was filled with the support structure. The density of the scaffold can be adjusted, and was set to the lightest level. Since the TangoBlackPlus™ rubber material was already installed, and since the top needed to be flexible, it was decided to use this. The results are shown in Figure 93.



(a) (b) (c)

Figure 93. SMETT 'P&P' prototype Mk II (a) complete, (b) top removed and (c) rubber sphere

There was unfortunately too little difference in stiffness between the spheres and the support matrix, meaning that even in the bare-handed condition, none of the spheres could be detected.

The material in the printer was then replaced with the hard plastic VeroBlue™. A new design was proposed, using a base modelled from the VeroBlue™ on which balls were supported on stalks of varying heights and locations, and with a matrix made from Room Temperature Vulcanising (RTV) Silicone (Silskin 10, MB Fibreglass; Shore A Hardness: 13) in an attempt to simulate the feel of human tissue. A disposable mould was produced from MDF and the silicone poured over the printed base to a height of approximately 20mm. The CAD model and finished prototype can be seen in Figure 94.

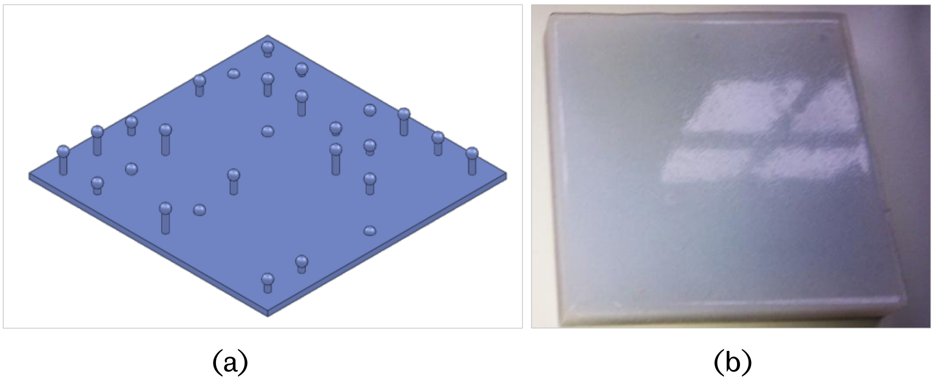
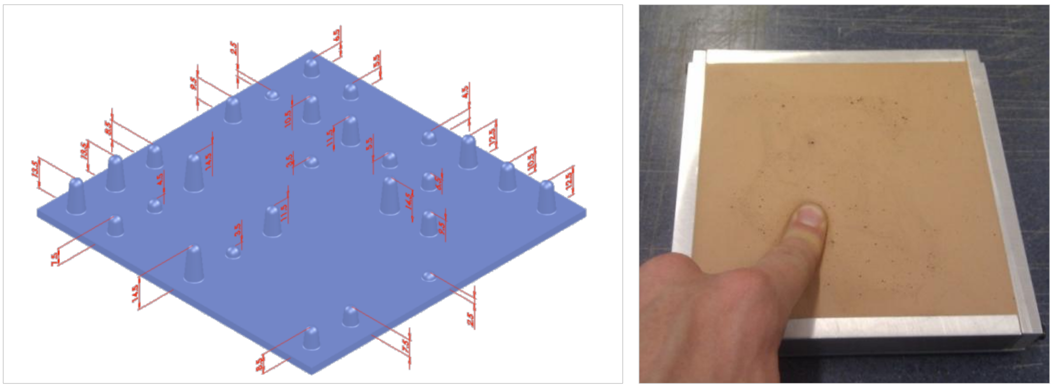

(a) (b)

Figure 94. SMETT 'P&P' Mk III prototype (a) CAD model and (b) after moulding

While there was some improvement in being able to feel the spheres near the surface, the silicone was too stiff and not very flesh-like.

Tests were carried out using silicone “deadener” fluid (dimethylpolysiloxane), which is used to soften RTV silicone and produce a fleshy “feel”. The proportions of deadener in the silicone were varied between 1:10 and 1:2, and it was initially decided that a 1:5 ratio of deadener to silicone resulted in the most useable and realistic stiffness. Flesh-coloured dye was also included to give a more realistic look and to obscure the location of the protrusions.

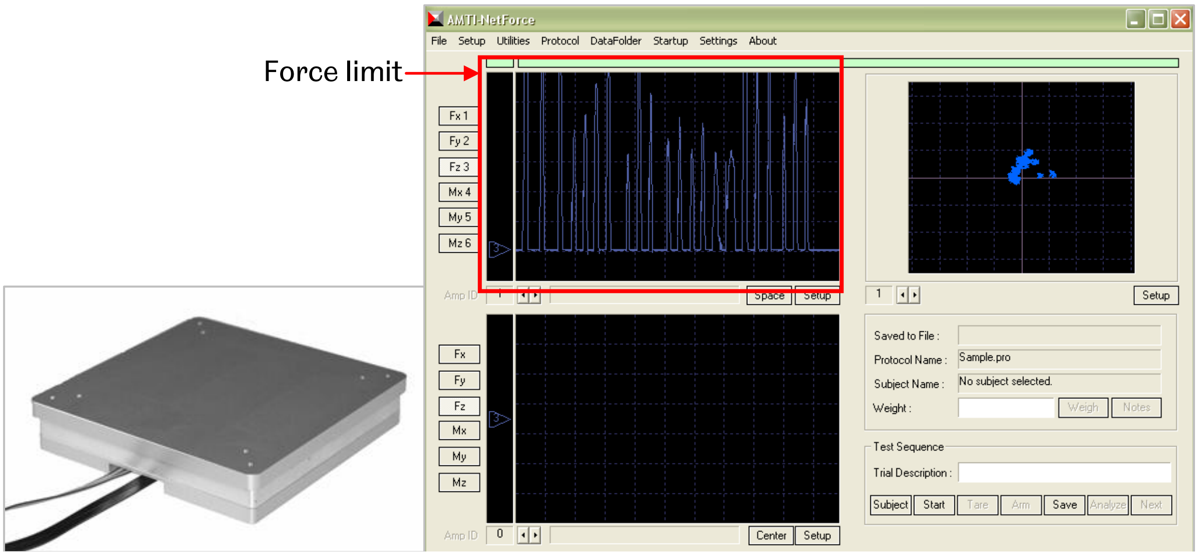
Final design. The Mark IV prototype is shown in Figure 95. The VeroBlue™ base was redesigned with conical protrusions to give greater strength and allow easier removal of the silicone. It consisted of a 140 x 140 x 2 mm plate with 27 conical protrusions with hemispherical ends of 5mm diameter. The heights of the top of the protrusions varied between 2.5mm and 14.5mm above the base, as shown in Figure 95. A permanent mould was produced from aluminium to avoid the model deforming more around the edges than the centre. The height of the edges above the base was 22mm, to give 20mm of silicone when full.



(a) (b)

Figure 95. SMETT 'P&P' Mark IV prototype (a) CAD model and (b) after moulding

Calibration. Preliminary tests were carried out in which the rig was placed on a 6-axis force plate (HE6X6-10, Advanced Mechanical Technology, Inc.; see Figure 96(a)) and the downward force when exploring the apparatus measured. It was hoped that limiting this force would prevent damage to the rig, injury to the participant, and prevent the participant just pressing harder until they felt the hard material.



Saved to File :
Protocol Name : Sample.pro
Subject Name : No subject selected.
Weight :
Trial Description :

(a) (b)

Figure 96. AMTI (a) HE6X6-10 force plate and (b) NetForce software

It was initially decided to use a 30N force in order to detect a reasonable number of protrusions. It was also decided to draw a grid onto the silicone to allow the researcher to identify which protrusions were detected and to assist the subject in staying within the row or column. The grid can be seen in Figure 101. A small mark was placed in one corner to aid with orientation.

7.6.2. Experimental design

Ethical approval. All the tests protocols, along with participant information sheets and consent forms, were submitted to the University of Sheffield Research Ethics Committee (REC) and received approval.

Participants. Test subjects were recruited from a number of sources. 39 subjects volunteered to participate. None had any known sensorimotor deficiencies or other major health problems. 34 were male and 5 were female, and their ages ranged from 20 to 59. One was a general surgeon.

Gloves. As with Test Battery 2, Finex PF latex and Finite P Indigo AF nitrile examination gloves were used. The within-subjects factor in the test was hand condition, consisting of three levels: 'No Gloves', 'Best-Fit Latex' and 'Best-Fit Nitrile'.

Glove selection. The subjects were allowed to choose the size of glove that fitted them best for each type, with some help from the researcher.

Procedure. The rig was placed on the force plate on a standard desk at which the subject was seated, and the force plate software was zeroed and the scale set so that the force limit lined up with the top of the window. The orientation of the rig with regard to the subject was randomised.

The force measurement was started, and the subject was directed to explore the rig column by column (they were not blindfolded), as in the 'Bumps' test, although the compliance of the material necessitated more of a 'prodding' technique.

The participant was told to watch the force plate display (see Figure 96) and to use as much force as necessary without going off the top of the scale. They were asked to signal verbally when they identified any hard lumps below the silicone.

Once they had explored the whole area, the force measurement was stopped, and the orientation of the rig was changed (there being four orientations in 90° increments). The whole process was repeated with each hand condition.

At the end of the testing, subjects were asked to rate their perceived performance in the three conditions on a scale of their choosing, so that a performance twice as good as another would get twice the score and so forth.

7.6.3. Issues and modifications

Nine participants were initially tested and a number of issues were found with the apparatus. The force required to detect even the larger protrusions was causing moderate to severe hand fatigue in participants, requiring them to rest between tests. It was also noted by the general surgeon that the force required was much greater than in a real medical examination. The stiffness of the silicone also appeared to increase over the time of the testing (5 days). It was therefore decided to remould the silicone with a higher ratio of deadener to silicone (3:10), and to reduce the force limit to 18N.

A further 20 participants were tested over nine days, and the rig again hardened over time. It was thought that this might be due to further curing of the silicone, despite the fact that the setting time stated by the manufacturer is 50 to 60 minutes. The deadener was not believed to leach in the same way that silicone oil (another softener) is reported to, and there was no evidence of leaching. This moulding was also somewhat inconsistent, with stiffer regions and parts that did not cure as well.

The ratio of deadener to silicone was again increased to 7:20 for a further moulding on which the final 10 participants were tested over eight days, keeping the limit at 18N.

7.6.4. Results

The results of the SMETT 'P&P' testing are shown in Figure 97. As well as the overall mean detection rate for the three hand conditions, the results are separated into the three mouldings.

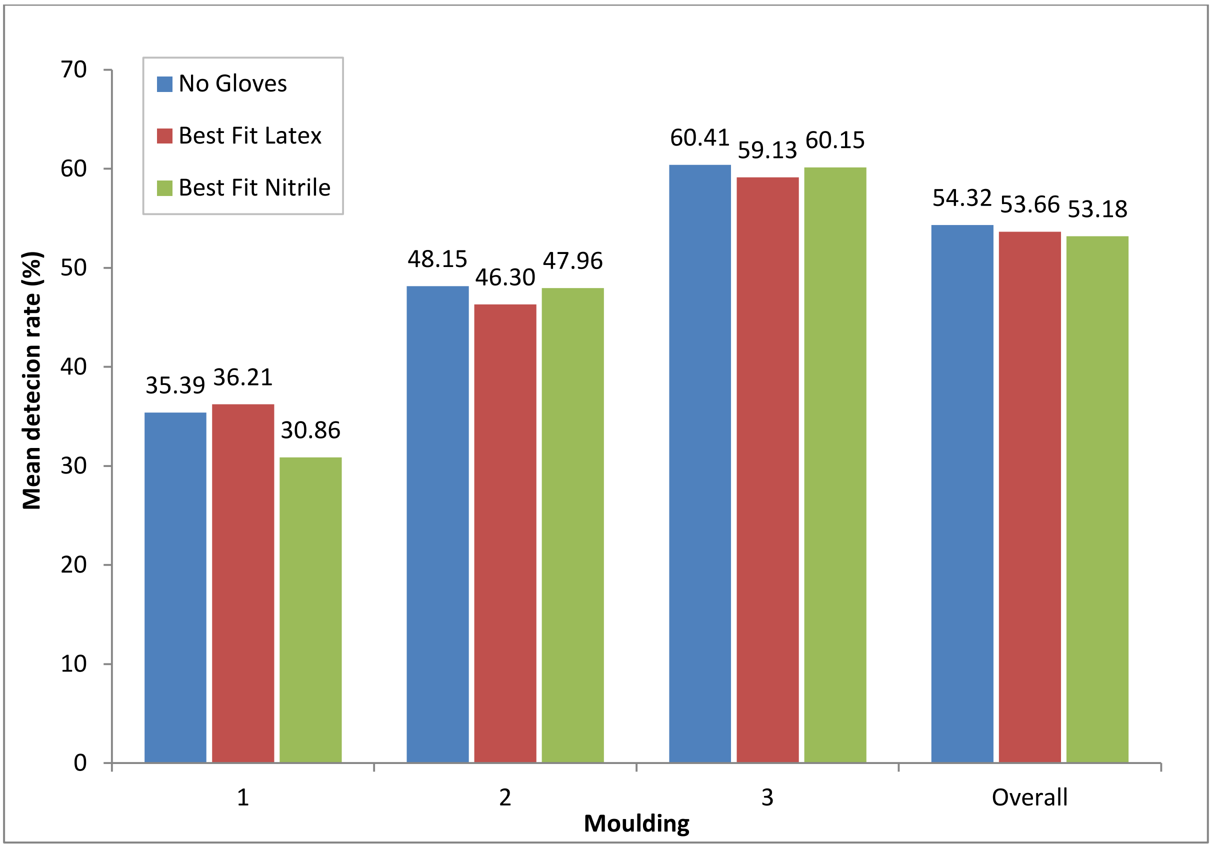


Figure 97. Mean detection rate across three mouldings of the SMETT 'P&P' test for the ungloved condition and two gloved conditions

Overall, subjects detected the most protrusions in the ungloved condition, followed by 'Best Fit Latex' and 'Best Fit Nitrile', but the trend was not the same across the mouldings. The individual scores were also normalised to remove the effect of changes in stiffness by dividing each score by the subject mean (across all treatments) and multiplying by the grand mean (all subjects, all treatments). The mean difference in performance between each of the gloved conditions and the 'No Gloves' condition, expressed as a percentage of the mean 'No Gloves' score, is shown for each moulding, overall and for the normalised scores in Figure 98.

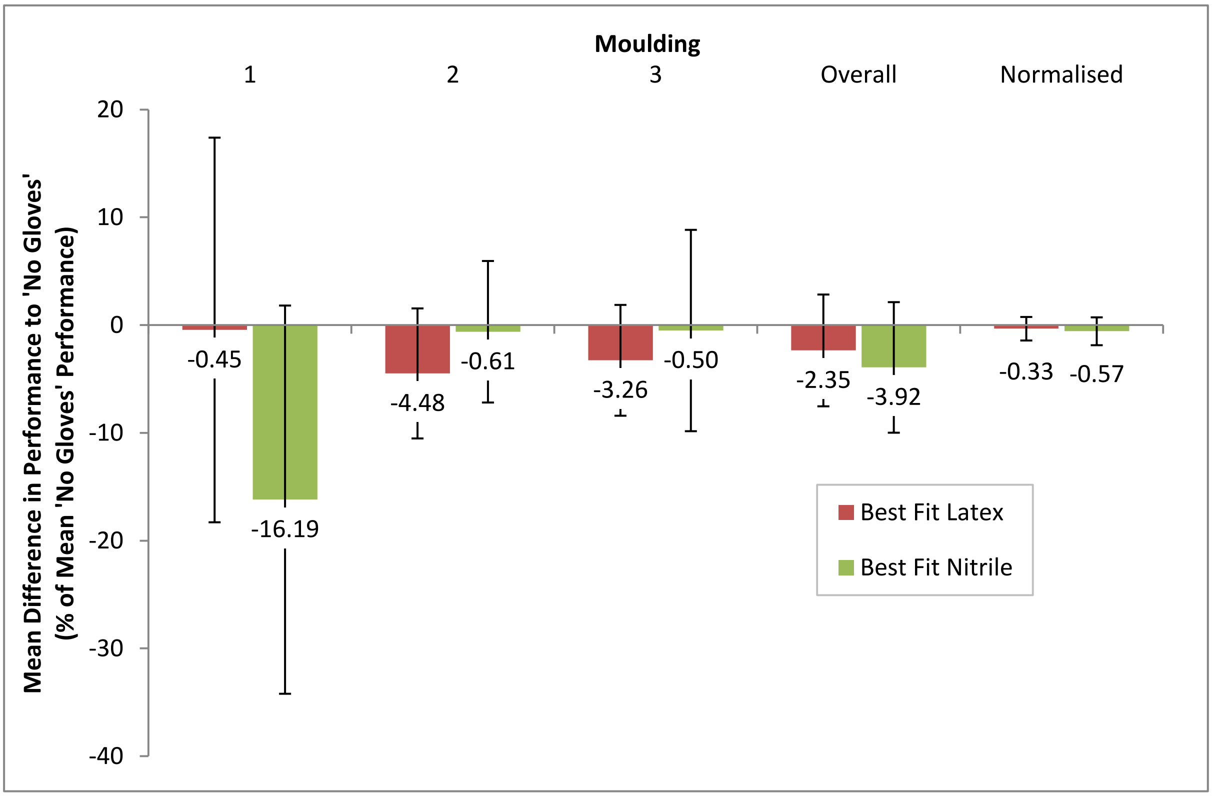


Figure 98. Relative performance of latex and nitrile gloves on SMETT 'P&P' performance across the different mouldings (with 95% confidence intervals)

From Figure 98, no statistical differences are apparent in any of the mouldings or in the overall or normalised scores. Numerical analysis (see Section 6.2.4) showed that overall results were normal for all treatments ($p \geq 0.60$), but confirmed that hand condition did not have a significant effect on detection rate ($p = 0.685$, ANOVA). Normalising the results as described increased the deviation of the gloved conditions from normality and decreased significance (p = 0.943 Friedman), and did not significantly alter the means (a reduction of 0.54, 0.08 and 0.47 for No Gloves, Best-Fit Latex and Best-Fit Nitrile respectively). In paired t-tests between the hand conditions, the overall scores all correlated well together (0.920-0.952, p < 0.001), suggesting the test is not giving random outputs, but measuring subject tactility. However, no paired differences were statistically significant (p ≥ 0.396; see Table 32).

Table 32. Significance of paired differences in 'SMETT' P&P tests

	Latex	Nitrile
No Gloves	NS (0.557)	NS (0.396)
Latex		NS (0.748)

Shapiro-Wilk tests for normality on each treatment and ANOVA tests for significance of hand condition were performed with the results separated into the three mouldings. The results are shown in Table 33.

Table 33. Statistical significance of hand condition for the three mouldings

Moulding	Normality	p (ANOVA)
1	0.258-0.553	0.248
2	0.216-0.505	0.304
3	0.007-0.443	0.991

Although hand condition is still not significant, the results suggest that the stiffer silicone produced more significant differences between glove types although, as previously noted, it felt unrealistic and caused hand fatigue very quickly.

Protrusion depth. One assumption of the test was that the detection rate would decrease with increasing depth of the protrusion below the surface, until a threshold depth where the protrusion could not be felt at the specified force limit. Because of the slight variation in volume of silicone with each moulding, a more accurate measure is the height of the top of the protrusion above the base. The depth below the surface can be approximated by subtracting this value from the full depth of 20mm. The relationship between protrusion height and mean detection rate across all mouldings is shown in Figure 99.

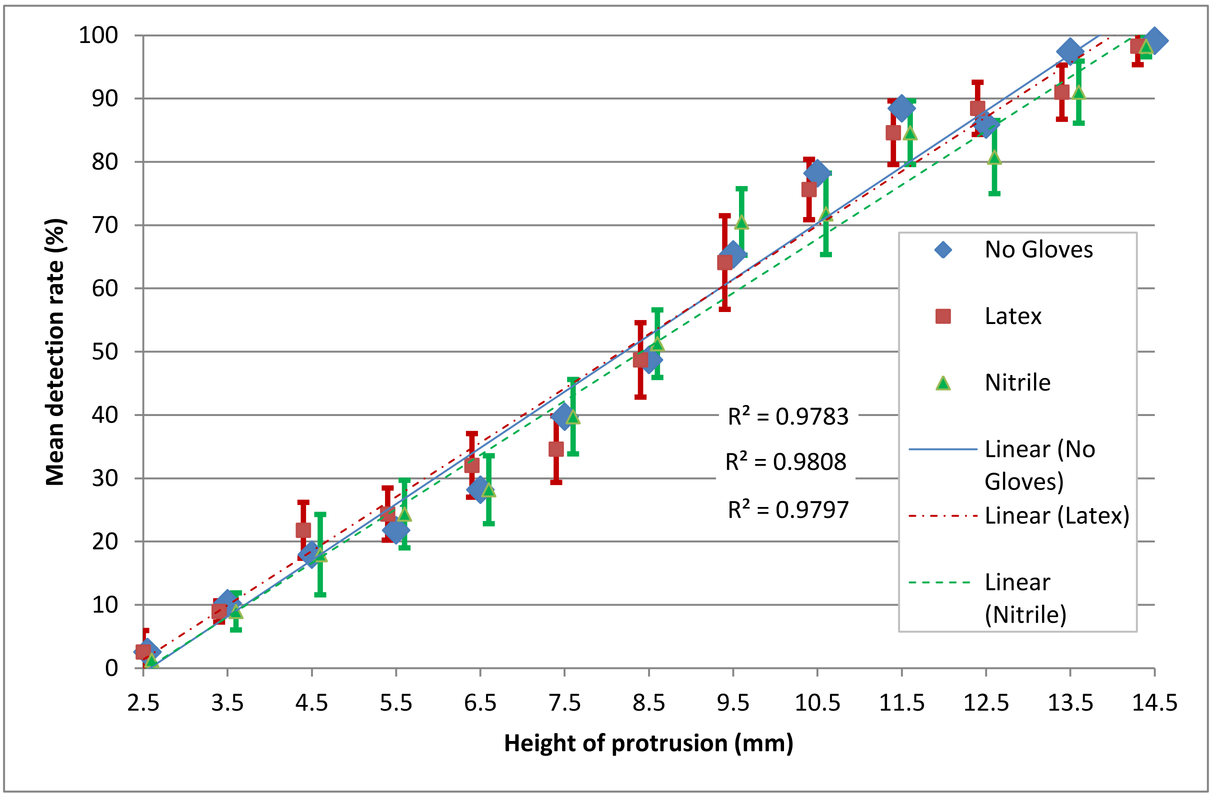


Figure 99. Mean detection rate (all mouldings) against height of protrusion from base with latex and nitrile examination gloves and ungloved, with 95% confidence intervals and linear trend lines with correlations (treatments separated horizontally for clarity)

There is a similar linear trend for each hand condition, with good correlation. The detection rates with the three hand conditions cannot be differentiated statistically at any height. In Figure 100, the results are separated into mouldings rather than hand conditions. It can be seen that there are large differences in detection rates between the final moulding and the first two, and that the variation in the results is largest for the first moulding.

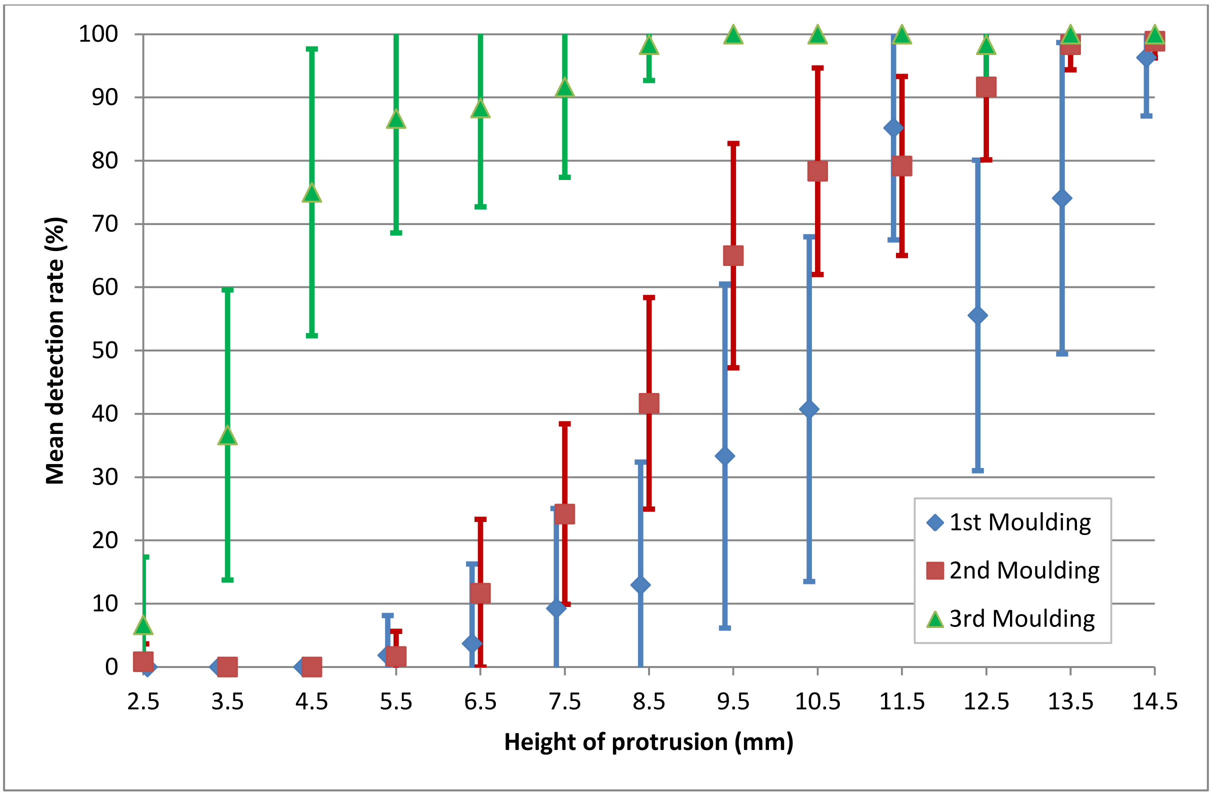


Figure 100. Mean detection rate (all hand conditions) against height of protrusion from base for each moulding, with 95% confidence intervals and linear trend lines with correlations (treatments separated horizontally for clarity)

There are some anomalous results, particularly for the 11.5mm high protrusion in the first moulding. A possible explanation could be found in the inconsistency of moulding, since the short working time of the silicone meant that thorough mixing was not always achieved before the silicone started to set, and air bubbles may also have formed under the surface. Location could also be a factor. It can be seen from Figure 95(a) that the two 11.5mm protrusions are near the centre, while the 12.5mm protrusions, which show a slightly below-trend detection rate in two of the mouldings, are on the edge. The angle of attack of the finger could mean that protrusions on the edge were more easily obscured, or the extra stiffness contributed by the frame could be a factor.

7.6.5.Stiffness testing

It is clear from the results that the most significant factor in detection rate was the moulding (p=0.000 in one-way ANOVA), the difference being apparently due to large variations in stiffness. It was therefore important for validation of the test to determine the hardening or stiffening behaviour of the silicone over time. Since standard hardness tests such as Shore would be difficult on material this soft (they require plastic deformation), a testing rig was designed to measure the force-deflection behaviour of the silicone.

It consisted of a digital force gauge (Mitutoyo 940-233E) that was mounted on a carrier and could be moved in the vertical axis via a threaded bar, and a digital indicator (Mitutoyo 575-123 Digimatic Indicator) that measured displacement and was fixed. The force gauge and digital indicator were linked via a custom-made part, shown in Figure 101, to a circular foot (ø = 11mm), so that the applied force and deflection of the silicone could be measured simultaneously.

Figure 101. Stiffness testing rig

Stiffness tests were performed on the silicone, beginning shortly after the third and final moulding had been poured.

Procedure. The tests were performed on sections of the rig where no protrusions existed, so that the silicone depth was approximately 20mm. Three measurements were taken in different locations and averaged. The foot was moved down until the bottom was just touching the surface of the silicone. The force gauge and digital indicator were zeroed. The foot was then moved down at an approximately steady rate so as to compress the silicone. (Some stress relaxation was apparent, and so a continuous and fairly high strain rate was used.) Measurements of force and deflection were taken at force increments of 0.5N, initially up to 2.5N, but increasing as the silicone hardened. The force was kept fairly low so as not to damage the silicone while tactility testing was still being carried out. Measurements were taken on 7 separate occasions up to 46 days after moulding.

Results. The force-deflection curves are shown in Figure 102. The stiffness can clearly be seen to increase with time. The relationship can be seen more clearly in Figure 103, in which the deflection under a 2N load is plotted over the period of the tests. The relationship approximates to a power law (R^2 = 0.936), so that the rate of change in stiffness reduces over time.

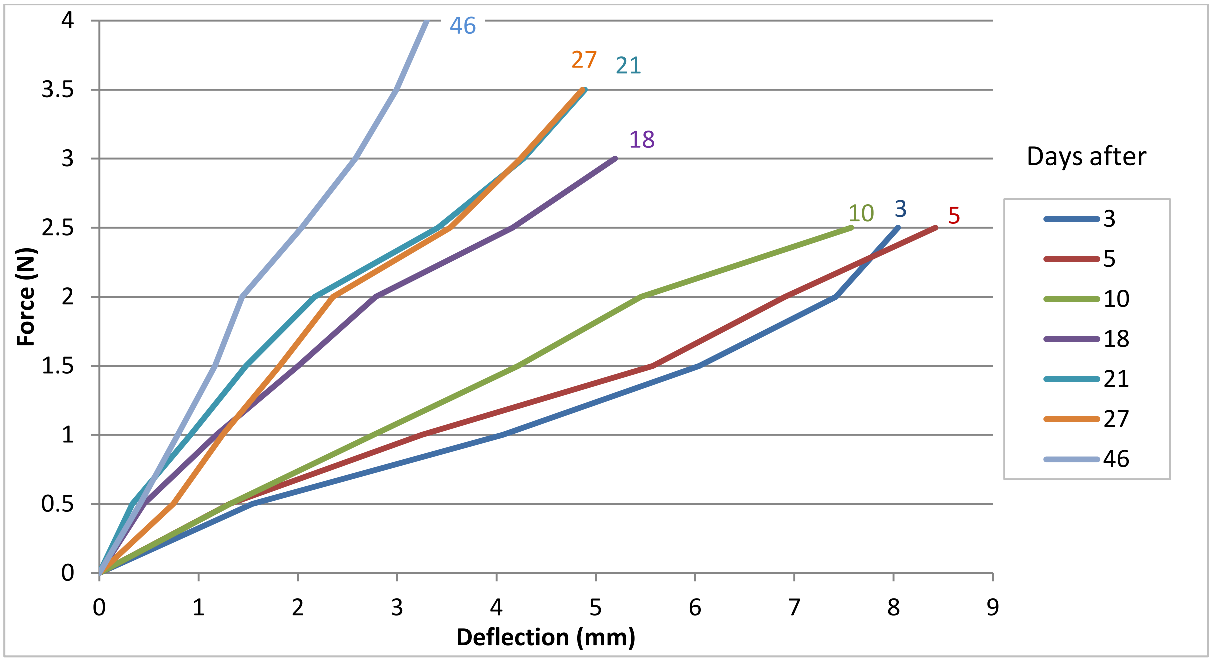


Figure 102. Force-deflection variation of P&P rig over time

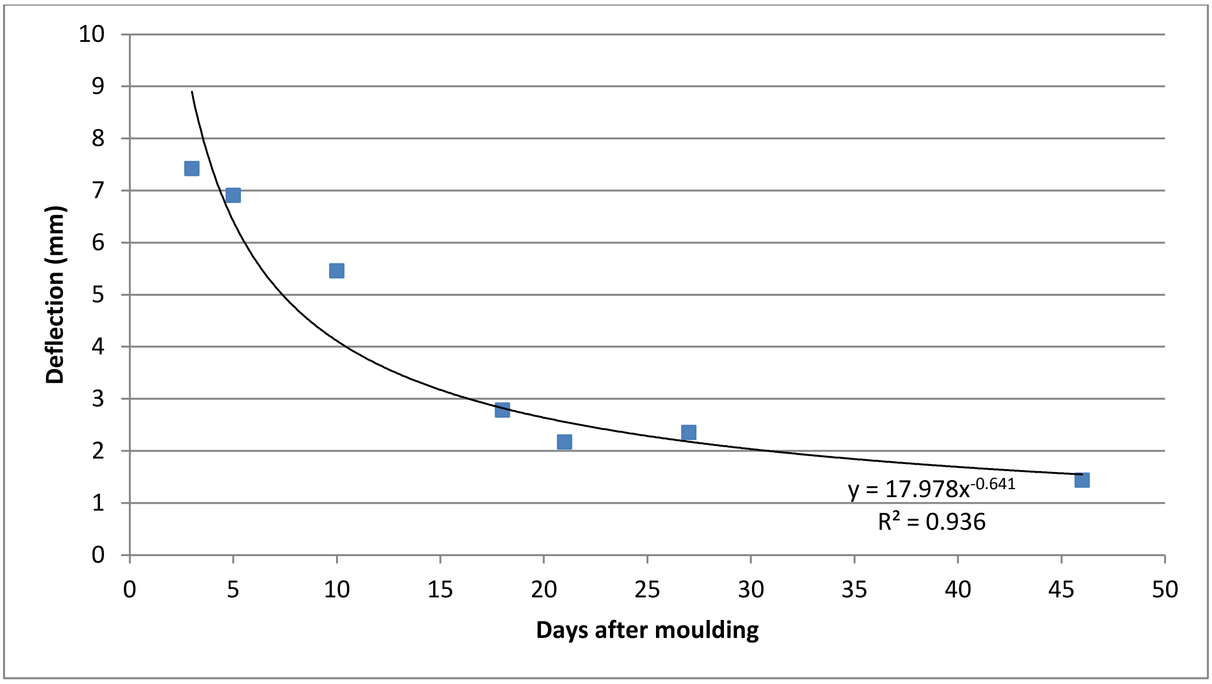


Figure 103. Variation in deflection of P&P rig under 2N load over time

In the final test, the force was increased steadily up to 24N to determine the force-deflection curve at larger forces comparable to those used in the tactility tests. The results are shown in Figure 104.

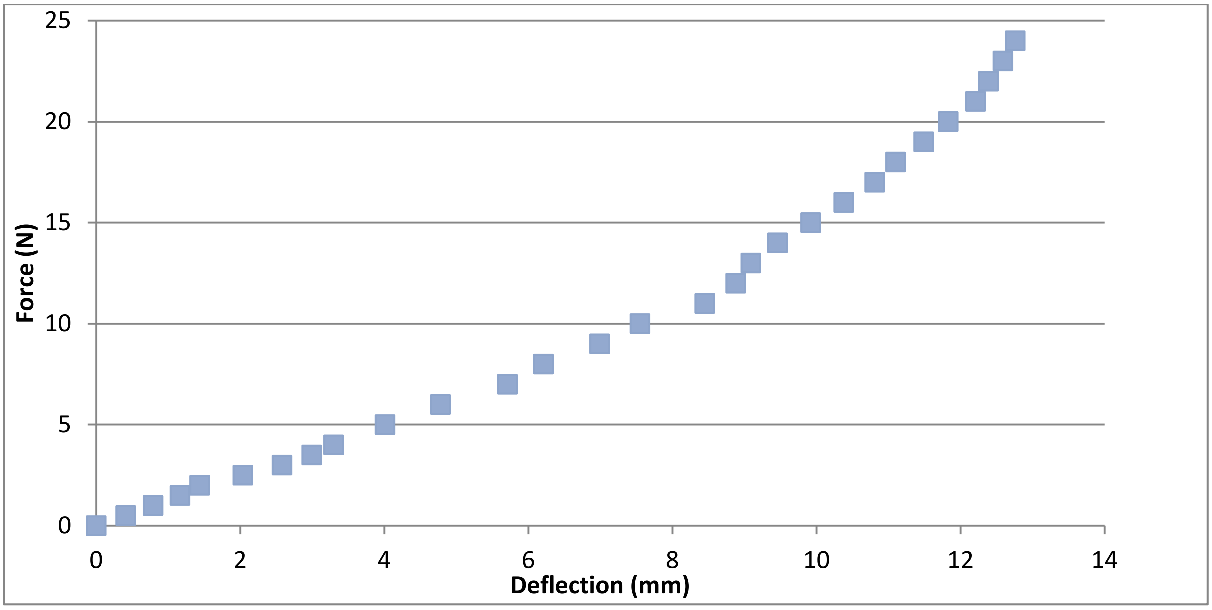


Figure 104. Force-deflection curve for final test (46 days after moulding)

The relationship between force and deflection (and hence between stress and strain) is nonlinear, with stiffness increasing at higher forces. This resembles the stress-strain relationship obtained from *in vivo* human calf measurements [178], although the stiffness is somewhat less for the silicone. For example, given that the diameter of the foot was 11mm and the depth of the silicone was 20mm, the strain at 0.2Nmm^{-2} was approximately 0.57, whereas strain values of less than 0.25 were obtained for the human calf at the same stress. However, the range of values was fairly large, and the range of stiffnesses throughout the human body would be expected to be much larger. Given the similarity in the curves, the silicone appears to be an acceptable simulation of body tissue for the purpose of this test.

At 18N, which was the force used in the last two mouldings, the deflection was approximately 11mm. Interestingly, this corresponds well with the height of protrusion (20 – 11 = 9mm) at which the detection rate started to drop below 100%.

Effect of stiffness on detection rate. 'P&P' tests were carried out 10 and 46 days after moulding using the same subject in an ungloved condition, and with the test in the same orientation. The detection rate was reduced by almost half from 85 to 48% for a stiffness increase of approximately 200%. This confirms what was observed in the larger-scale testing in the difference between mouldings.

7.6.6.Further investigations and refinement of the test

As with the ‘Bumps’ test, a number of possible issues with the apparatus and procedure were identified during the testing, and further investigations were carried out to assist in refining the test. As mentioned previously, there were some concerns that, because of the way the silicone was compressed to well below the top of the frame, the angle of attack of the finger might mean that those protrusions around the edge might be missed in certain orientations (see Figure 105). The added stiffness contributed by the frame might also make detection of edge protrusions harder than those in the centre.

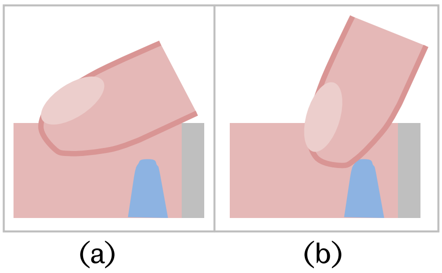


Figure 105. Effect of technique on detection in 'P&P': (a) flat and (b) perpendicular

It was also considered that the technique used – whether the terminal *phalanx* was parallel or perpendicular to the surface – might have an effect on detection in the same way as with the ‘Bumps’ test. Finally, the maximum allowed force will clearly affect the detection rate, and will also affect the level of hand fatigue.

These issues were explored in a number of tests on an individual subject, who was not naïve to the test. All the tests were done bare-handed, 46 days after moulding, on the third moulding. The treatments for each test are shown in Table 34.

Table 34. Treatments in three variables for SMETT 'P&P' testing

Test	Orientation (degrees)	Force (N)	Technique
1	0	18	Flat phalanx
2	270	18	Flat phalanx
3	180	18	Flat phalanx
4	90	18	Flat phalanx
5	0	18	Fingertip
6	270	18	Fingertip
7	180	18	Fingertip
8	90	18	Fingertip
9	0	6	Flat phalanx
10	90	12	Flat phalanx
11	180	24	Flat phalanx
12	270	30	Flat phalanx

Results. The mean detection rates for each of the four orientations are shown in Figure 106. Differences of up to 7.5% in detection rate occurred in different orientations. Of the 11 protrusions that were detected around the edge, one at 10.5mm was detected in all four orientations with the fingertip, and only one orientation with the finger flat. The remaining six protrusions above 9.5mm were detected in all eight tests. Where those below 9.5mm were detected, it was always with the fingertip. Only two of the six protrusions not on the edge were detected in some orientations and not others.

There was much more difference in the effect of orientation when the fingertip was used than when the *phalanx* was flat against the surface. An explanation for this is not immediately obvious. It can be seen from Figure 107 that the mean detection rate across all orientations was significantly higher when using the fingertip than when using a flat *phalanx*, most likely due to higher pressure caused by the smaller area, in turn allowing a greater strain of the silicone for a given force. The apparent differences in detection rate between orientations may be due simply to the fact that protrusions on the limit of detection are only detected in a proportion of tests, whatever the orientation.

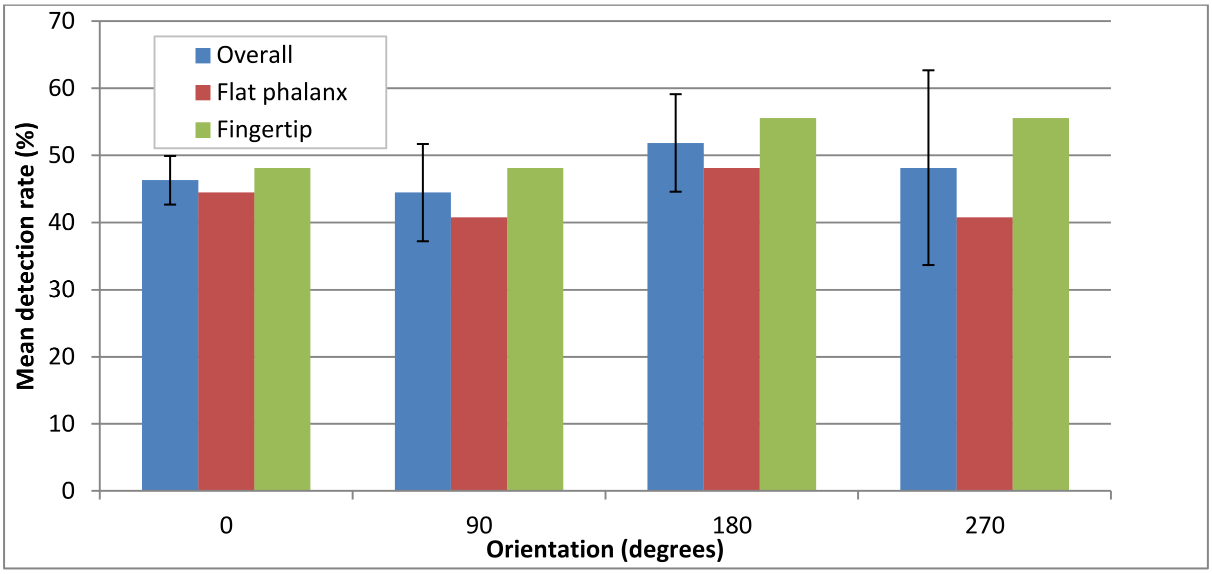


Figure 106. Effect of orientation on mean detection rate (both techniques, 18N)

While orientation was already randomised in the test procedure to eliminate any learning effects, these results show that technique is a significant factor, and subjects should be instructed to stick to one technique throughout the tests. If the technique is to be specified, it is suggested that the flat *phalanx* is used, since more fatigue occurred when using the fingertip, and more damage to the rig from fingernails is possible. In order to ensure when using this technique that the protrusions around the edge are not missed, it is proposed that the area of the silicone be enlarged to include a buffer area around the edge.

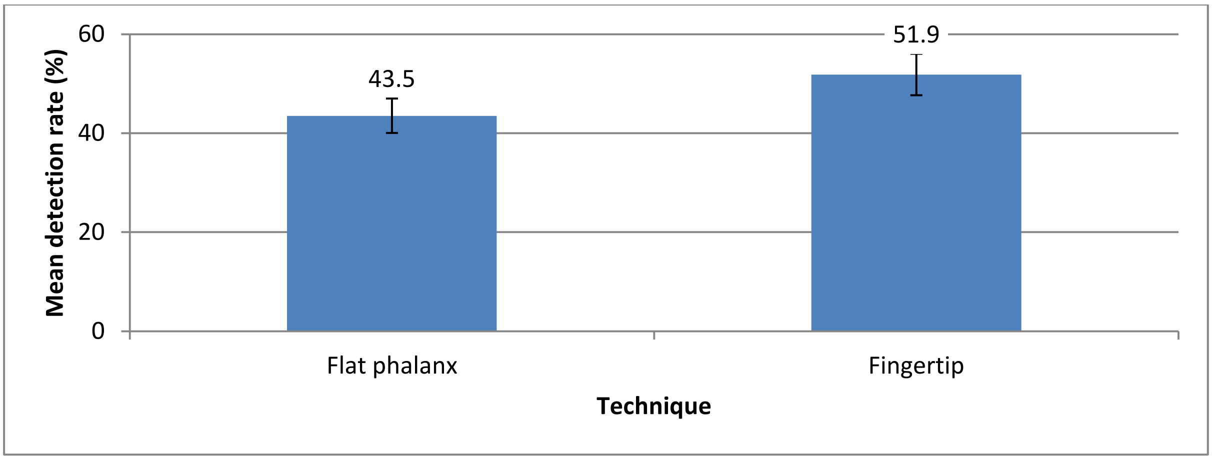


Figure 107. Effect of technique on mean detection rate (4 orientations, 18N)

The effect of increasing the force can be seen in Figure 108. While there is clearly a lower detection rate at the lowest force and a higher detection rate at the highest force, the performance appears to be fairly similar within the range 12-24N. Further investigation with more candidates (so that any effect of orientation can also be removed) is needed to draw any firm conclusions, but a lower force would certainly be preferable in terms of reducing fatigue, if there is little reduction in detection rate. One thing that was not considered was the strain rate, since the stress relaxation that occurs in silicone means that applying the same maximum force at different rates may get different results. This may be explored in future study, since the strain rate is difficult to regulate when applying a manual force.

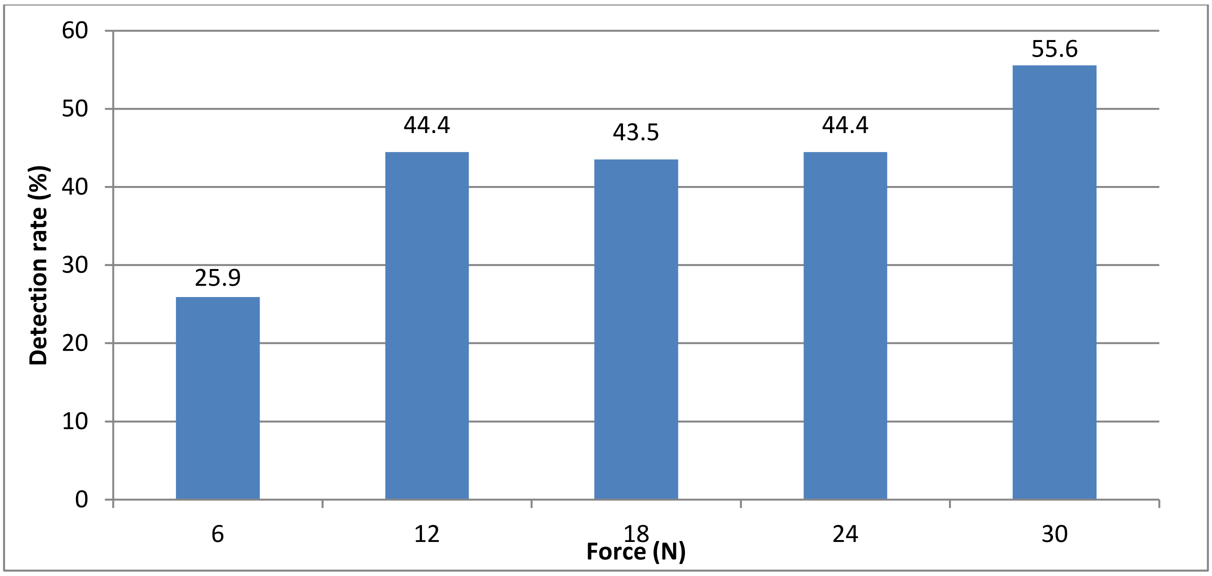


Figure 108. Effect of force on detection rate (flat phalanx, 18N score averaged over 4 orientations)

7.6.7. Discussion

The test found no significant differences in performance as a result of wearing gloves. Differences in stiffness where protrusions occur are felt as a change in the resistive force opposing the downward movement of the finger. It seems probable that this involves more haptic than tactile sensing (i.e. muscle sensors rather than skin), in which case, adding a thin barrier between the finger and the silicone is unlikely to have as significant an effect on performance as it does on the 'Bumps' test. The difficulties with stiffening over time, requiring regular re-moulding, also make this test fairly impractical for regular glove testing. It is, however, a reasonable simulation (at low force levels) of medical examination.

7.7. Pulse Location Test

7.7.1. Study of existing technology

The heart pumps blood around the body by peristalsis – the contraction of the muscles in a wave that forces the blood around the system. The pressure in the system increases when the left ventricle contracts to pump blood out (this higher pressure is known as the ‘systolic pressure’) and decreases when the right ventricle relaxes to allow blood back in (this lower pressure is known as the ‘diastolic pressure’). The difference between these two pressures is known as the ‘pulse pressure’. Because of the elastic nature of blood vessels, this variation in pressure results in a variation in diameter of the vessels, which is what is felt as a pulse in the arm.

Training equipment has been designed to allow medical trainees to practise palpating the pulse and drawing blood samples. An Arterial Puncture Arm such as that shown in Figure 21 was examined to determine how the pulse was created. The pulse simulation equipment consists of latex tubes which are filled with liquid. At each end is a reservoir. After the tubes are filled, one end is clamped off, and a squeeze bulb is used to create a pressure pulse. The tubes sit in grooves in the polymeric core of the arm which means the pulse cannot be felt except for at two designated locations where the firm polymer is replaced with low density foam that squashes on palpation, allowing the pulse to be felt.

While this is an effective training tool, it has some limitations as far as testing is concerned. Since the location of the pulse cannot be varied, the participant will know after the first attempt where to expect the pulse. This makes it much easier to detect, and makes verification of detection harder. Furthermore, the squeeze bulb does not allow accurate variation of the pulse pressure, which is necessary to find the threshold of detection for a given hand condition.

To overcome these problems, a new design was proposed in which the pulse could be sent through any one of a number of "vessels", and in which the pulse pressure and rate could be controlled. For consistency of flow, it was proposed to use a peristaltic pump (EYELA Micro-Tube Pump MP3) to create the pulse. The concept was tested using a single latex tube with a foam block and polystyrene, and it was found that the pulse could be clearly felt, so it was decided to proceed to with the design of the rig.

7.7.2. Manifold design

In order to be able to vary the location of the pulse, a switch was needed. It was decided to have five locations, to provide enough uncertainty as to the location over the course of a few tests. A five-way manifold was designed in SolidWorks and built on the Objet printer using VeroBlue™. However, testing showed that the rubber gasket was unable to contain the water at the required pressure while allowing rotation of the switch. A five-way switch used for aquarium "airstones" was used instead (see Figure 109). This performed adequately, although it was prone to a small amount of leakage, requiring refilling of the system before every test session.

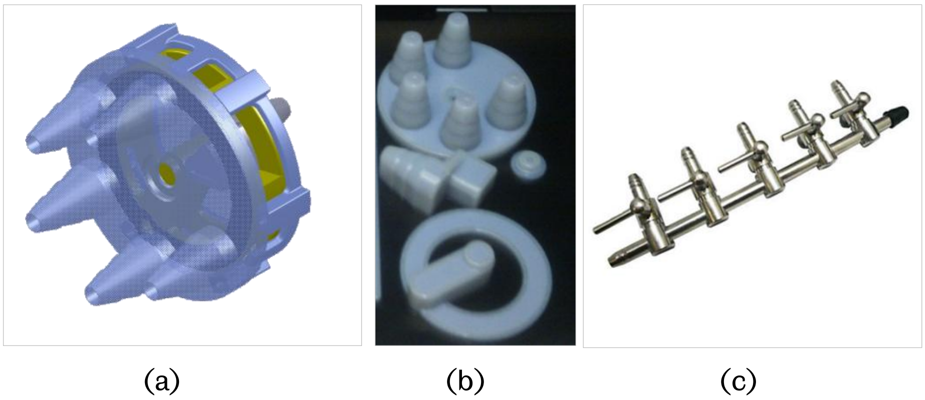
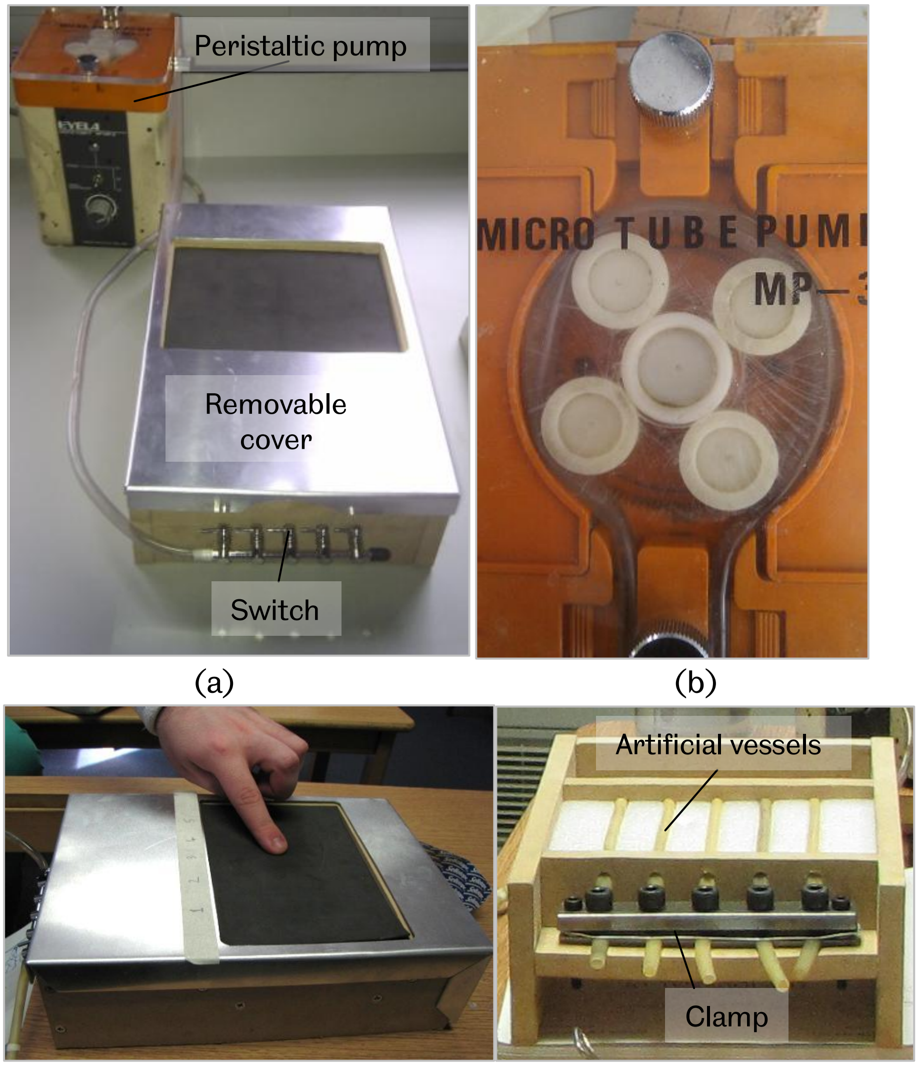

(a) (b) (c)

Figure 109. Pulse rig manifold (a) SolidWorks design, (b) printed parts, (c) 5-way aquarium air switch

7.7.3. Final Test Rig

The final test rig can be seen in Figure 110. The artificial vessels are made from latex tubing ($^{3}/_{16}$" ID, $^{1}/_{32}$" wall thickness), which is flexible enough to cause palpable changes in diameter with pressure changes. The diameter was chosen to match the existing Arterial Puncture Arm, but is also close to the diameter and thickness of the radial artery [179]. The tubes sit in v-section grooves cut into a block of low-density rigid packing foam, so that they just protrude above the surface. The tubes are then covered in a 1.5mm sheet of neoprene rubber sponge, which was chosen for its low stiffness that gives more of a flesh-like feel than stiffer rubbers such as silicone or vinyl (used in the Arterial Puncture Arm) and allows enough compression to feel the vessels beneath it.

A case was constructed from medium-density fibreboard (MDF) through which the latex tubes are fed from the five-way switch. After passing through the foam, the tubes are clamped through a flexible plate which is bolted to the casing and allows each tube to be opened and closed individually (Figure 110). An aluminium lid was manufactured to hide the workings (where fluid flow could be seen) from the subject, and to improve the aesthetics. The five-way switch is connected to the peristaltic pump via a stiffer plastic tube. To set up the apparatus, the cover and rubber sponge sheet were removed, all five valves were opened and the system was filled with water from the pump end (by placing the loose tube end in a jar). The clamp was released and water was allowed to flow through the ‘vessels’ until a steady flow was achieved and no bubbles could be observed in the tubes. The clamp was then tightened and the pump end clamped with a plastic crimp to seal the system. The lid and rubber sponge sheet were replaced.



(a) (b)

(c) (d)

Figure 110. Pulse Location Test: (a) with cover; (b) pump configuration; (c) location technique; (d) cover removed

Calibration. The aim of the test was obviously to simulate as closely as possible the feel of a human pulse. The pump motor speed could be varied, and the number of pulses per revolution could be altered by changing the number of cogs that squeeze the tube (Figure 110). This had the additional effect of changing the pulse pressure, which could also be varied by screwing in the two halves that formed the outer walls of the pump, thus increasing the constriction of the tubes by the cogs.

The pulse rate was set to approximately 90 bpm, which falls within the range of normal pulse rates for adults at rest [180]. Experiments were then carried out to determine the range of pulse pressures that could be achieved. It was found that adjusting the screws did not give a satisfactory range of pressures – the adjustment was very fine and within half a turn the pulse could go from fairly strong to non-existent. This would not allow for measuring the threshold pressure at which a pulse could be detected.

New pressure adjustment system. A number of possibilities for providing pressure adjustment were explored, but the only one that was found to be viable was a method based on changing the volume of fluid in the system. The clamps at each end of the tubes ensure that the system is closed i.e. there is no fluid flow in or out. This means that when the peristaltic pump squeezes the tube, it simply compresses the fluid down the line, which creates a temporary pressure increase that is relieved when the cog runs off the tube. This pressure increase is felt as a pulse, the strength of which depends on the amount of compression of the fluid. Thus, for a given stroke volume, decreasing the volume of fluid in the system will increase the pulse pressure.

The variation in fluid volume was achieved by attaching a length of the latex tubing to the end of the five-way switch. The tube was marked with tape at 11 locations, 45mm apart. To set the pressure, the tube was pinched at a mark using thumb and forefinger. The apparatus can be seen in Figure 111.

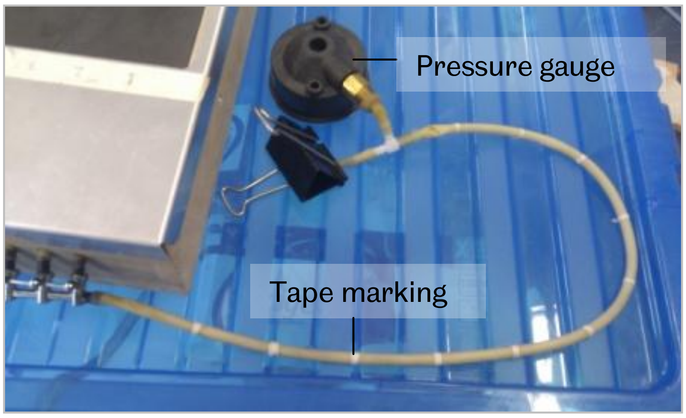


Figure 111. Pressure adjustment mechanism for Pulse Location Test

Attempts were made to measure the pressure using a 60in.H20 gauge, attached as shown in Figure 111, but the fluctuations were too high, and even with the pump turned off, the gauge did not seem to read a consistent pressure. This is something that would be worth exploring if the test is developed further to enable quantification of the pressure threshold. It was discovered during preliminary testing that while the tube provided enough volume change to differentiate between gloved and ungloved threshold, variation between candidates was larger. It was therefore necessary to calibrate the starting pressure by adjusting the screws as described so that the candidate could definitely feel the pulse at the highest pressure and definitely not feel it at the lowest pressure. The calibration was done ungloved as the expected most-sensitive condition, making sure that the highest pressure was some way above the threshold to allow for loss of sensation with gloves.

7.7.4. Experimental design

Procedure. The subject was seated in front of the test, with the five-way switch facing away from them. After following the set-up and calibration procedures described, the researcher selected a random 'vessel' for the first test (unseen by the subject). The valve connected to this vessel was left open while the other four were closed. The vessels had been numbered 1 - 5 for ease of identification. The pump was switched on and the researcher pinched and held the pressure adjustment tube at one of the marks (usually starting with the one closest to the switch). The subject was then asked to state the number of the vessel in which they could feel a pulse, if any.

The procedure for determining the pressure threshold was based on the Rapid Threshold Procedure™ (see Section 7.2.2), with a slight modification to save time. After a successful identification of the vessel number, the pressure was reduced to a lower mark, and after an error or non-identification, the pressure was increased. The location of the pulse was then changed to one of the other four vessels, randomly selected and the test repeated. The first mark at which both a successful and an unsuccessful attempt were made was taken as the 50% threshold pressure (in the original procedure, the test is always continued after a successful identification, regardless of whether previous attempts at that level had been successful, and is only stopped after a failure). Because time was a crucial factor in medical practitioner testing, it was felt this adjustment was necessary, and that little, if anything, was lost in the way of accuracy. The number of the division was recorded (1 being the closest to the switch and hence the highest pressure, 11 being the furthest and hence lowest).

The test was included in Test Battery 2. For further details of the experimental design, including participant recruitment, glove selection, location, perception scoring and fit measurement, see Section 6.2.3.

7.7.5. Results

Since for each subject the rig was re-calibrated and the absolute value of pressure could not be obtained, absolute scores would have little relevance. Therefore, only the difference in performance of each gloved condition to the ungloved condition was calculated (performance being defined as the pressure threshold as measured by number of divisions from the switch). The mean differences for latex and nitrile are shown in Figure 112 as a percentage of mean 'No Gloves' score, with 95% confidence intervals.

Although the results are displayed as a percentage to enable easier comparison with other tests, it should be noted that, since pressure could not be measured absolutely, a 50% reduction in 'performance' should not be taken to mean that the pressure threshold was twice as high, or that the *cutaneous sensibility* was half as much. It can, however, be seen that the mean pressure threshold was much lower (i.e. performance was better) when ungloved than when wearing examination gloves, and latex performed slightly better than nitrile.

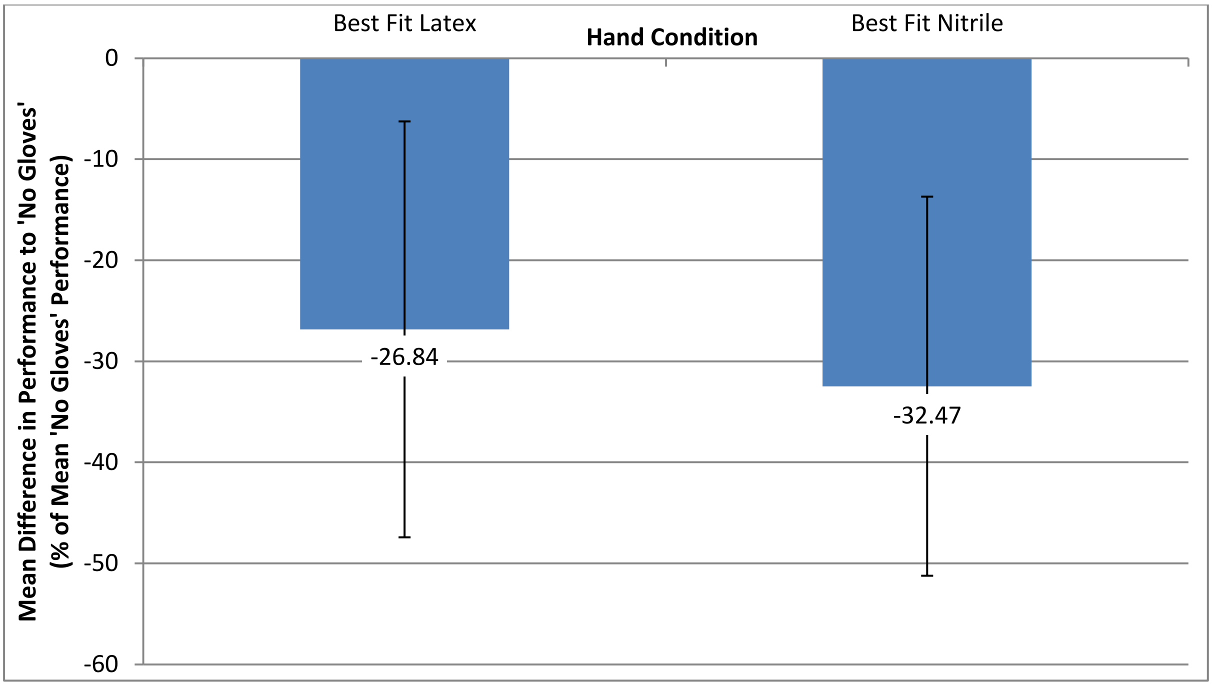


Figure 112. Comparison of latex and nitrile examination gloves performance in pulse test, measuring mean difference to 'No Gloves' score as a percentage of mean 'No Gloves' score, and including 95% confidence intervals

Statistical analysis. Results for the three conditions showed no significant deviation from normality (p≥0.224). Repeated-measures ANOVA showed that hand condition had a significant effect on test score (p=0.014). Results of the paired t-tests between the three conditions are shown in Table 35, and a schematic of the significance of the differences is shown in Figure 113.

Table 35. Significance of paired differences in the Pulse Location Test

	Latex	Nitrile
No Gloves	S (0.021)	S (0.004)
Latex		NS (0.671)

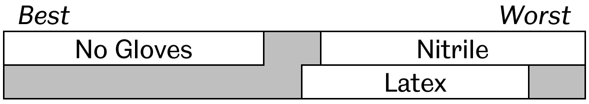


Figure 113. Schematic of significance of differences between hand conditions for the Pulse Location Test

The ungloved performance is clearly significantly better than gloved performance, but no significant differences between nitrile and latex were found.

7.7.6. Discussion

The results match those of the Semmes-Weinstein monofilaments, which found that ungloved tactility was significantly better, but that single-layer gloves could not be separated. The gloves act as a barrier that attenuates the tactile signals from the pulsating vessel, but the similarity in thickness of the gloves means the attenuation effect is very similar. Given that significant differences in the ability to locate a pulse were found between the ungloved condition and the gloved conditions, the test is certainly promising.

The test therefore has value in assessing improvements in tactility for new glove designs with the aim of closing the gap to the ungloved performance. However, it is important for validation of future glove comparisons that absolute values for the threshold are obtained, whether in terms of pulse pressure through a gauge, or in terms of number of divisions on the pressure adjustment tube. In order to achieve the latter, the tube length needs to be increased to give a larger range of pressures.

The pump was not ideal in being limited in speed and pressure adjustment, and the cogs wore fairly easily so that they began to slip, causing the pulse to be irregular. A more robust and user-friendly pumping and pressure adjustment system could be designed, based on the same principles (peristalsis, variation of fluid volume). Whether it is possible to differentiate the performance of medical gloves is uncertain. With more accurate measurement and finer gradations of pressure, the significance of the differences found might be increased.

7.8. Dental Probe Test

7.8.1. Initial design and purpose

Figure 114. Dental Probe Test apparatus (reproduced from [158])

A test was originally designed by Chris Dinsdale at the School of Clinical Dentistry, The University of Sheffield [158] to investigate the forces used by Dental Reference Officers when performing basic periodontal examinations (BPE) and to investigate the differences in probing forces with three types of probe. The equipment (shown in Figure 114) consists of a manikin model of the lower jaw with a gingival mask produced from silicone with pre-determined pocket depths, mounted on a load cell. The model was modified with amalgam used to simulate sub-gingival deposits.

7.8.2. Redesign and programming

In testing the effect of medical gloves on tactility, the task was somewhat altered to focus on the identification of sub-gingival deposits. Originally, the model contained only one simulated deposit. In order to allow some repetition in the testing with different gloves, without learning behaviour being dominant, it was necessary to add more simulated deposits. The locations are shown in Figure 115. The load cell was connected to a data acquisition PC and a measurement routine was written in LabVIEW which recorded the vertical load on the manikin at a rate of 2000 samples per second. The force values were plotted on a live chart and also recorded in a text file. The model was calibrated using laboratory masses.

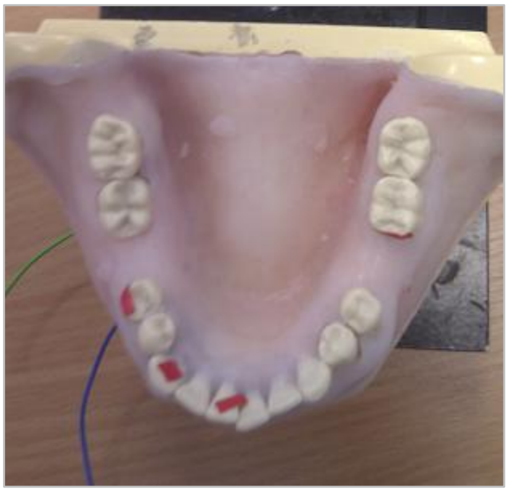


Figure 115. Locations of simulated sub-gingival deposits (red labels mark teeth and indicate sides under which 'deposits' exist)

7.8.3. Experimental design

Ethical approval. All the tests protocols, along with participant information sheets and consent forms, were submitted to the University of Sheffield Research Ethics Committee (REC) and received approval.

Participants. Test subjects were recruited from a third year dental course. 32 students volunteered to participate. None had any known sensorimotor deficiencies or other major health problems.

Gloves. As with Test Battery 2, Finex PF latex and Finite P Indigo AF nitrile examination gloves were used. The within-subjects factor in the test was hand condition, consisting of three levels: ‘No Gloves’, ‘Best-Fit Latex’ and ‘Best-Fit Nitrile’.

Glove selection. The subjects were allowed to choose the size of glove that fitted them best for each type. All participants had sufficient experience wearing medical gloves to decide the best-fit size for themselves.

Procedure. The manikin model was separated into three sextants, as is common in dental practice, consisting of the rearmost three on each side and the central six (see Figure 116). Each subject then performed three tests, each one having a sextant and a hand condition randomly assigned to it. The subject was given a round periodontal probe (CPITN-C, Dental Express) and asked to perform a six-point periodontal pocket examination, looking for sub-gingival deposits, using a continuous movement (i.e. not going back over areas) and to report any deposits they found, indicating verbally while continuing the examination. They were also warned not to put any pressure on the teeth except with the probe, since the accepted technique is to 'bridge' on other teeth for stability, which would obviously alter the force readings. Instead, a wooden block with a non-slip surface was provided for them to place where comfortable and lean on. Besides this modification, they were otherwise told to treat it as they would a real examination in terms of the probing forces applied. Before each test, the force measurement was zeroed. Data acquisition was then started and the subject was instructed to commence. When they had finished, they indicated verbally, and acquisition was stopped.

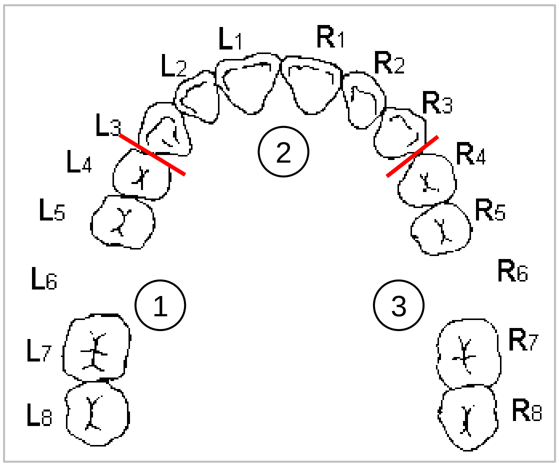


Figure 116. Separation of manikin teeth into sextants

7.8.4. Data analysis

The 96 text files were processed using a MATLAB script (Appendix D) based on the function peakfinder.m (Copyright (c) 2009, Nathanael C. Yoder, all rights reserved.) that determined the major peaks in the probing forces in both the downward and upward directions based on how far above the surrounding data they were (thus ignoring spurious peaks due to noise). Upward (negative) forces were recorded because, where deposits existed, the probe would catch on a ledge during the upward stroke. The means of the maxima and minima were then calculated. A typical force-time trace for a single test is shown Figure 117.

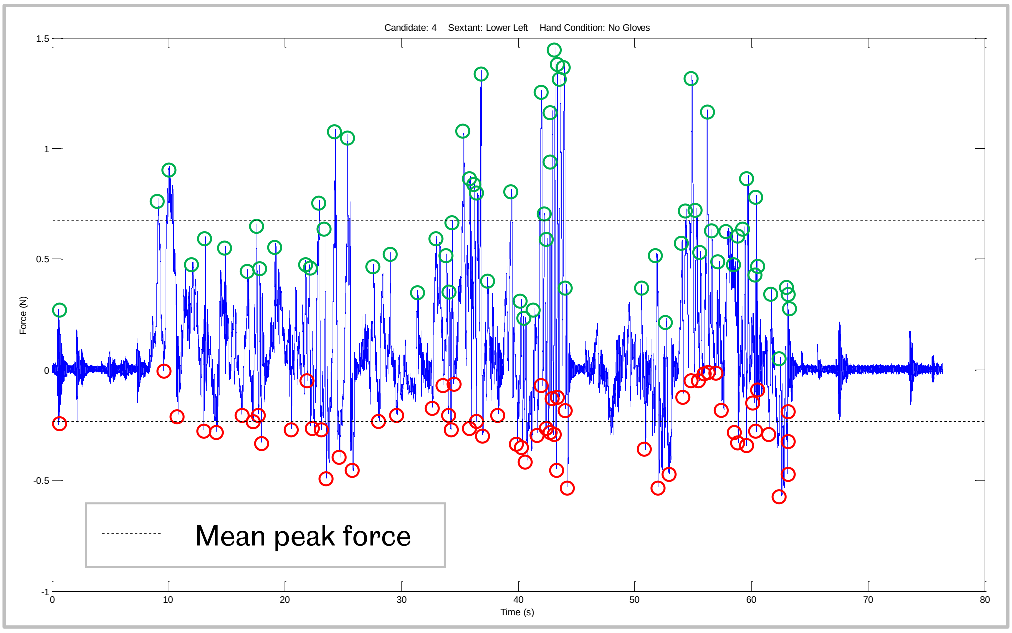


Figure 117. Typical force-time plot for dental probe test with individual maxima (green) and minima (red) and mean peak upward (negative) and downward (positive) probing forces as calculated in MATLAB

It was initially intended to additionally assess performance by how accurately subjects identified the simulated deposits. However, the number of false identifications was so high for most subjects that the results had little meaning, and so were not analysed. The level of inaccuracy may have been due to subjects' inexperience in clinical dentistry (the test was practised with a consultant who was more able to identify the correct areas), and may have also been due to the worn nature of the manikin, with false ledges being created from excessive scratching with the probe over time.

7.8.5.Results

The mean peak push (downward) and pull (upward) force for the ungloved, latex and nitrile conditions are shown in Figure 118. The mean differences for each of the gloved conditions to the ungloved condition are shown in Figure 119.

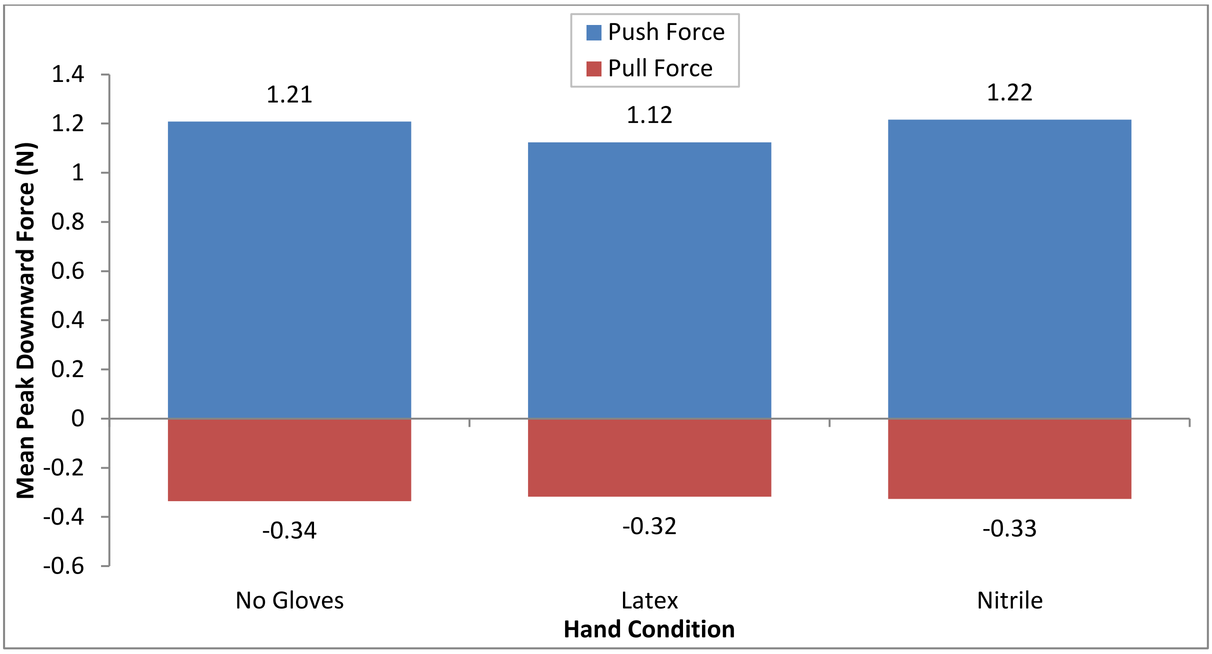


Figure 118. Mean peak push (downward) and pull (upward) force in dental probe test

It can be seen that there are only small differences in mean peak force between the treatments in both directions, although the probing force was lowest in both directions when wearing latex gloves. The mean peak downward force was almost four times the mean peak upward force. It can be seen from Figure 119 that the confidence intervals are much larger than any differences.

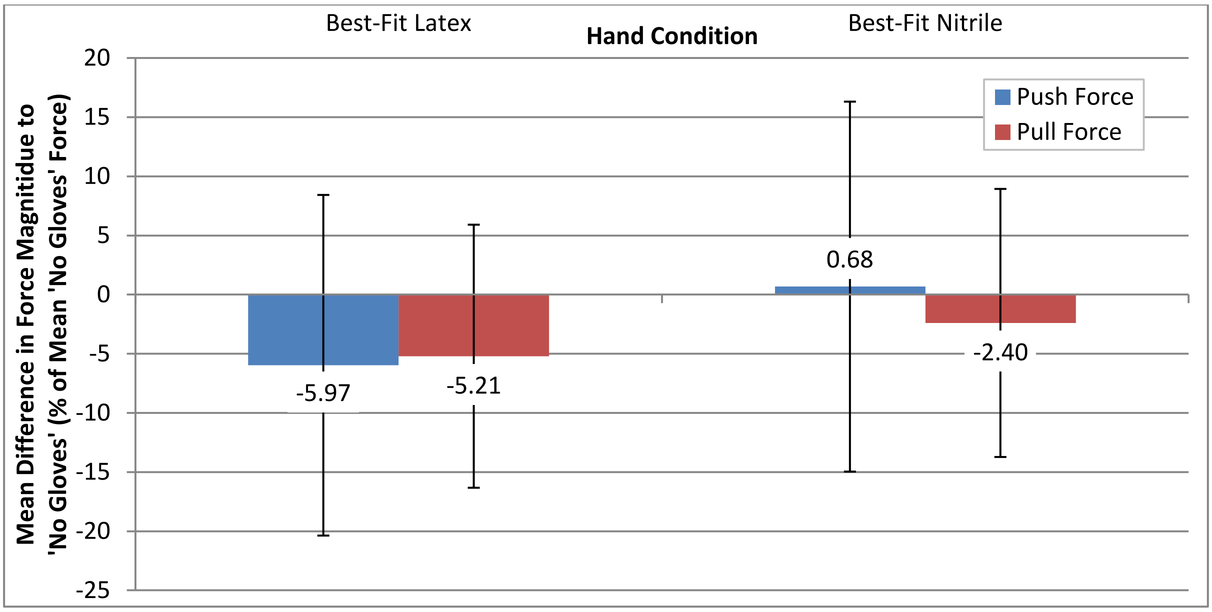


Figure 119. Mean Differences in probing force (upward and downward) with gloves to the ungloved condition (percentage of mean ungloved force, with 95% confidence intervals)

All data sets (separated into treatments) showed significant non-normality (p<0.036), so the Friedman test for significance was used. It showed that hand condition did not significant affect the average maximum force (p=0.417) or average minimum force (p=0.417). Removing the data points most deviated from normality and performing a repeated-measures ANOVA did not increase the significance.

Although order and sextant were randomised, the nature of randomisation means that, given the small number of tests performed, the distribution may not be even. Paired tests (Wilcoxon Signed Ranks) for order (Table 36) showed that the mean peak probing force was significantly lower in the first test than in the second for both downward and upward strokes and significantly lower in the first test than the third for upward strokes. Sextant was significant for maximum force, but not for minimum (p=0.607 – Friedman). The results of the paired tests are shown in Table 37.

Table 36. Significance of differences for test order in dental probe test

Average Max. Force	2nd	3rd
1st	S (0.018)	NS (0.262)
2nd		NS (0.254)

Average Min. Force	2nd	3rd
1st	S (0.014)	S (0.009)
2nd		NS (1.000)

Table 37. Significance of differences for sextant in dental probe test

Average Max. Force	Centre (L3-R3)	Right (4-8)
Left (4-8)	NS (0.108)	S (0.047)
Centre (L3-R3)		S (0.004)

The effects of order and sextant on the overall results based on the spread between the three glove conditions of each variable are calculated in Table 38 and Table 39. It can be seen from Table 38 that the spread of test order may have skewed the results to produce a lower mean downward force for ‘No Gloves’ than the gloved conditions, but the sextant should not have significantly affected results.

Table 38. The effect of test order on mean peak force for the three hand conditions

	No Gloves	Latex	Nitrile	**Av. Max.**	**Av. Min.**
1	14	10	8	1.06	-0.293
2	5	13	14	1.31	-0.338
3	13	9	10	1.18	-0.349
Expected Average Max. Force (N)	1.15	1.19	1.21		
Expected Average Min. Force (N)	-0.32	-0.33	-0.33		

Table 39. The effect of sextant on mean peak force for the three hand conditions

	No Gloves	Latex	Nitrile	**Av. Max.**	**Av. Min.**
Left	9	13	10	1.19	-0.323
Centre	11	10	11	1.32	-0.325
Right	12	9	11	1.03	-0.333
Expected Average Max.	1.18	1.19	1.18		
Expected Average Min.	-0.33	-0.33	-0.33		

The results were adjusted based on the calculated effects of the test order and sextant on each individual score, which increased the significance of the effect of hand condition, but the p values for mean peak push and pull force were still above the significance level (p = 0.072 for push force, 0.168 for pull force – Friedman). It can be seen from Figure 120 that the main effect of the adjustment is to increase the difference between the gloved conditions and the ungloved condition, so that both mean peak push force and mean peak pull force when wearing latex gloves border on being significantly less than those applied when in the ungloved condition.

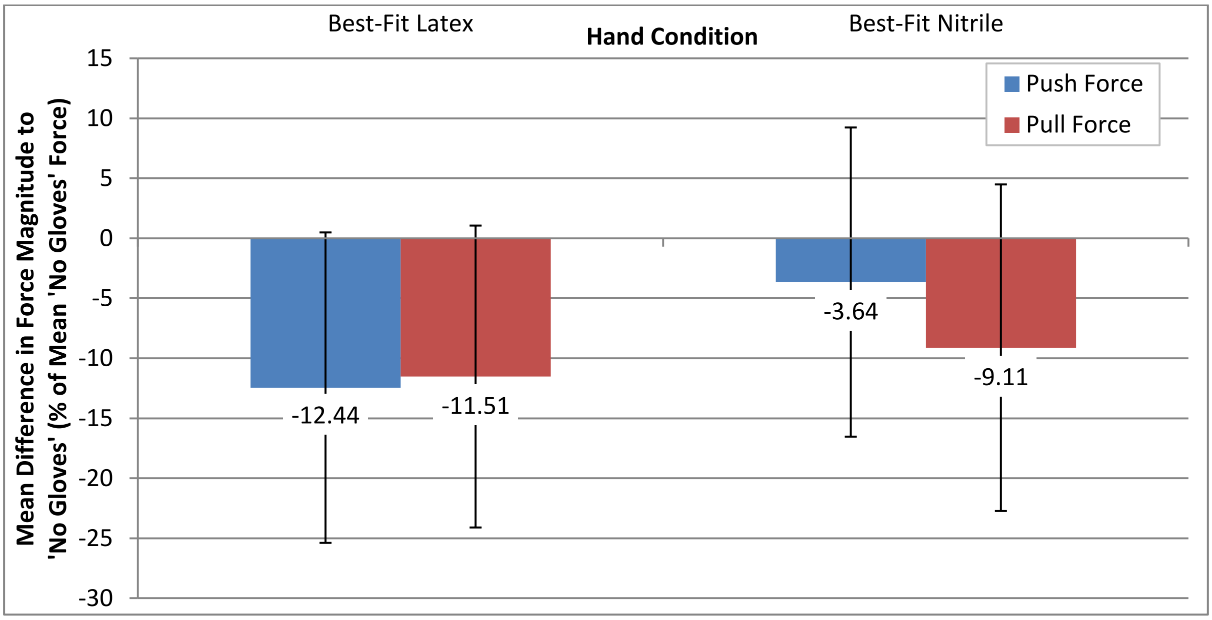


Figure 120. Mean Differences in probing force (upward and downward) with gloves to the ungloved condition (percentage of mean ungloved force, with 95% confidence intervals, adjusted for sextant and test order)

7.8.6.Discussion

The results show that the test is not an effective way to compare the performance of two or more medical gloves. Even the differences between ungloved and gloved performance were not significant. It was expected that, as in the Semmes-Weinstein monofilament tests, although differences between gloves of similar thicknesses might be hard to detect, the glove barrier would provide some attenuation of the tactile signal and hence reduce tactility compared to bare hands. However, the indirect nature of the tactile response (being transmitted through the probe) means that the tactile signals are primarily vibratory rather than deformation-based.

The primary nerve endings that receive vibratory signals (Pacinian corpuscles) are located deep in the subcutaneous tissue (see Section 2.2.1), more than a millimetre below the surface. Since examination gloves are generally around 0.1mm thick, the added layer will make little difference to the strength of signal received by the nerve ending. Furthermore, because of the generally static nature of the hand/glove/tool contact, the fit and conformability of the glove will have less of an impact than in dynamic tests such as the SMETT 'Bumps', where relative movement of layers and wrinkling of glove material can distort the signals.

In terms of the realism of the simulation, the forces used (approximately 120g downward force) were much higher than those recommended (20-25g [158]) and even than those recorded by Dinsdale (approximately 80g). Some subjects commented that they were using higher forces than they would on human teeth because they knew they were not causing pain and wanted to 'do well' in the test, despite being asked to treat it as a real examination. Adjustments to the method might be possible to increase the realism, but if, as the results suggest, the test does not show differences in performance between gloves, it is not worthwhile development in this context.

7.9. Conclusions

Five new tactility tests were developed: the Roughness Perception Test, the Simulated Medical Examination Tactility Test (SMETT) 'Bumps', the SMETT 'Princess and the Pea' (P&P), the Pulse Location Test and the Dental Probe Test. Experiments using these tests, along with the Semmes-Weinstein Monofilaments, were carried out on subjects wearing different types of examination glove and ungloved.

In two of the tests (SMETT 'P&P' and Dental Probe Test) a significant effect of hand condition was not found. In the other four, tactility was found to be significantly better in the ungloved condition than when gloved, but no significant differences in performance between glove types were found. The Semmes-Weinstein Monofilaments testing indicated a reduction in tactility when "double-gloving" with latex gloves compared to a single layer.

The Roughness Perception testing showed that both spatial and vibratory sensing were impeded by medical gloves, but that differences between gloves were clearer at larger particle diameters, where spatial coding was dominant. Accordingly, the SMETT 'Bumps', which tests the ability to feel small raised bumps on a surface, produced by far the most significant differences between the gloves ($p = 0.065$), with the Indigo nitrile gloves out-performing the Finex® latex gloves. The difference in thickness between the gloves was put forward as a possible explanation for this result, supported by the reduction in tactility seen with a double layer of gloves in the Semmes-Weinstein Monofilaments testing.

8. Grip and Friction

8.1. Introduction

Interviews with practitioners (Chapter 4) highlighted concerns about the frictional properties of gloves and their effect on the ability to grasp tools as well as performing other friction-dependent tasks. Grasping is a complex control operation involving not only muscular actuation but also sensory feedback in various forms. Since surgeons in particular often grasp instruments for extended periods, grasping forces will have an effect on muscle fatigue and stress levels. It is important, therefore, to study the frictional properties of medical gloves and how they affect grasping forces. This must also take into account the effect of lubrication, since gloves will often be contaminated with bodily fluids such as blood or saliva, which will tend to reduce friction and increase the incidence of slips and drops.

In Chapter 5, two existing methods (Sheffield finger friction rig and Polyco friction angle rig) were chosen for further testing with examination gloves, and it was also decided to develop a pinch-grip test based on Westling and Johansson's rig [28, 32]. An anthropomorphic device (artificial hand) was also proposed that would enable repeatable testing of grip forces on real tools. This chapter details the development and validation of these tests with medical gloves. The results of hand dynamometer testing with nitrile gloves carried out by Tasron [160] at the University of Sheffield are also analysed.

8.2. Practical Evaluation of Existing Tests

8.2.1. University of Sheffield finger friction rig

Previous studies [181, 182] at the University of Sheffield have attempted to characterise examination glove friction using the University of Sheffield finger friction rig [25] (Figure 121).

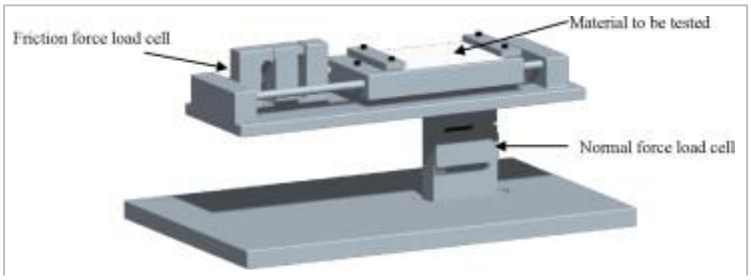


Figure 121. University of Sheffield finger friction rig (reproduced from [21])

The rig consists of a horizontal platform, attached to a frame via two load cells, measuring normal and shear forces applied to the platform. When a finger is drawn across the surface, the two load cells measure normal and friction force. By examining the two force profiles (Figure 122), the coefficient of dynamic friction can be determined. A MATLAB script was used to select a flat section of the profile (i.e. where the finger was sliding steadily) and take an average of each force. The coefficient of friction, μ, was calculated as:

$$\mu = \frac{Friction\ force}{Normal\ force}$$

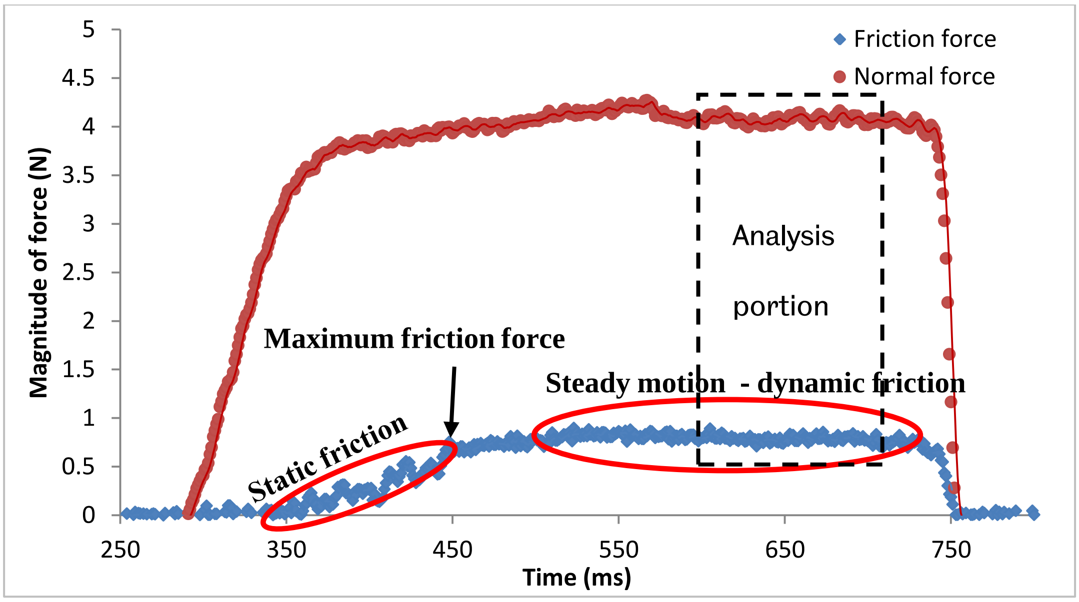


Figure 122. Example force profile for finger friction test

The test procedure was as described in [21], except that the index finger rather than the middle finger was used:

> The finger approached the surface so that the largest area of the upper section (*distal phalanx*) of the finger was presented parallel to the surface, the angle between the surface and the finger, after the *interphalangeal joint*, ranged between 22° and 26°. The finger was then moved linearly towards the body. The volunteer tried to keep a constant speed for each test, counting slowly from 1 to 5 from start to finish of the slide. This method has been proven as a simple but effective method of maintaining a constant speed for each test (approximately 0.014–0.028 ms−1). The materials were attached to the friction rig using adhesive tape and a clamping system.

Both Chadwick [181] and Denton [182] tested Finex® (latex), Finite P Indigo (nitrile) and Finity (vinyl) gloves and an ungloved finger on smooth stainless steel in dry and wet conditions. The wet conditions were created by dipping the gloved finger into a container of water just before performing the test. Both tests used only one subject, who selected the best-fitting size for each glove. A number of tests were performed with each glove at different levels of normal force.

Results. The results of Chadwick's dry and wet friction tests are shown in Figure 123 and Figure 124 respectively. Power curves have been fitted to the results in accordance with common finger friction models [21], but there is not sufficient data to draw strong conclusions about the shape of the curves.

The highest coefficient of friction in dry conditions occurred with the latex gloves, followed by nitrile, with vinyl having the lowest coefficient of friction.

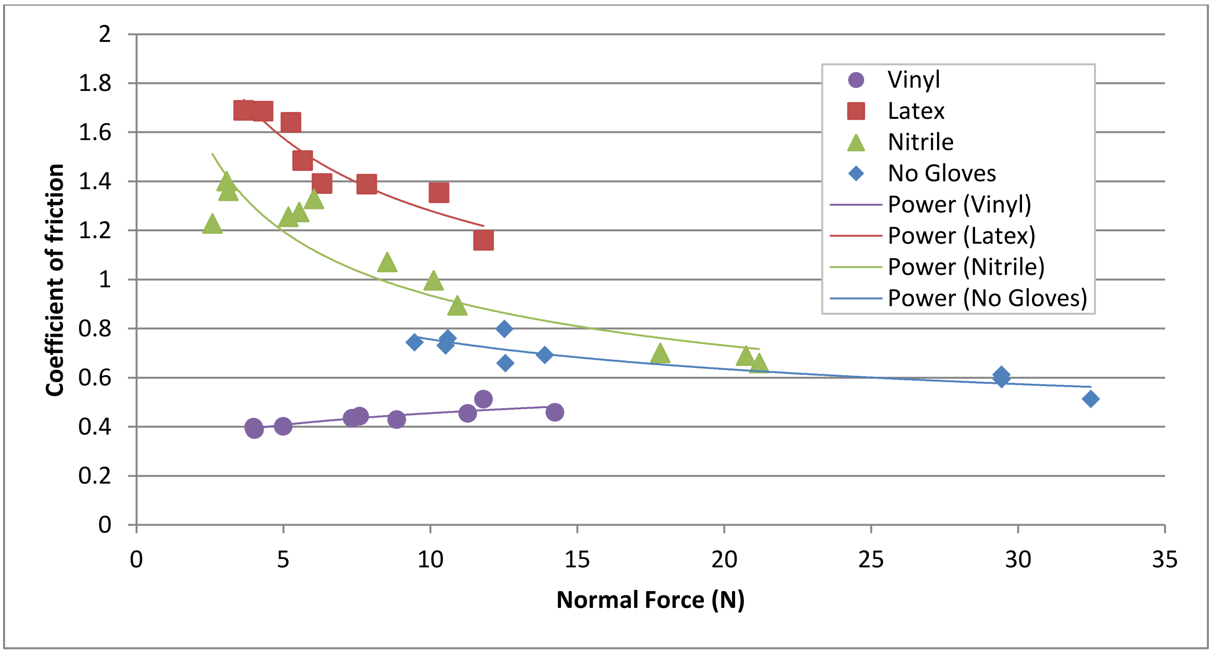


Figure 123. Dry friction results from Chadwick's [181] tests

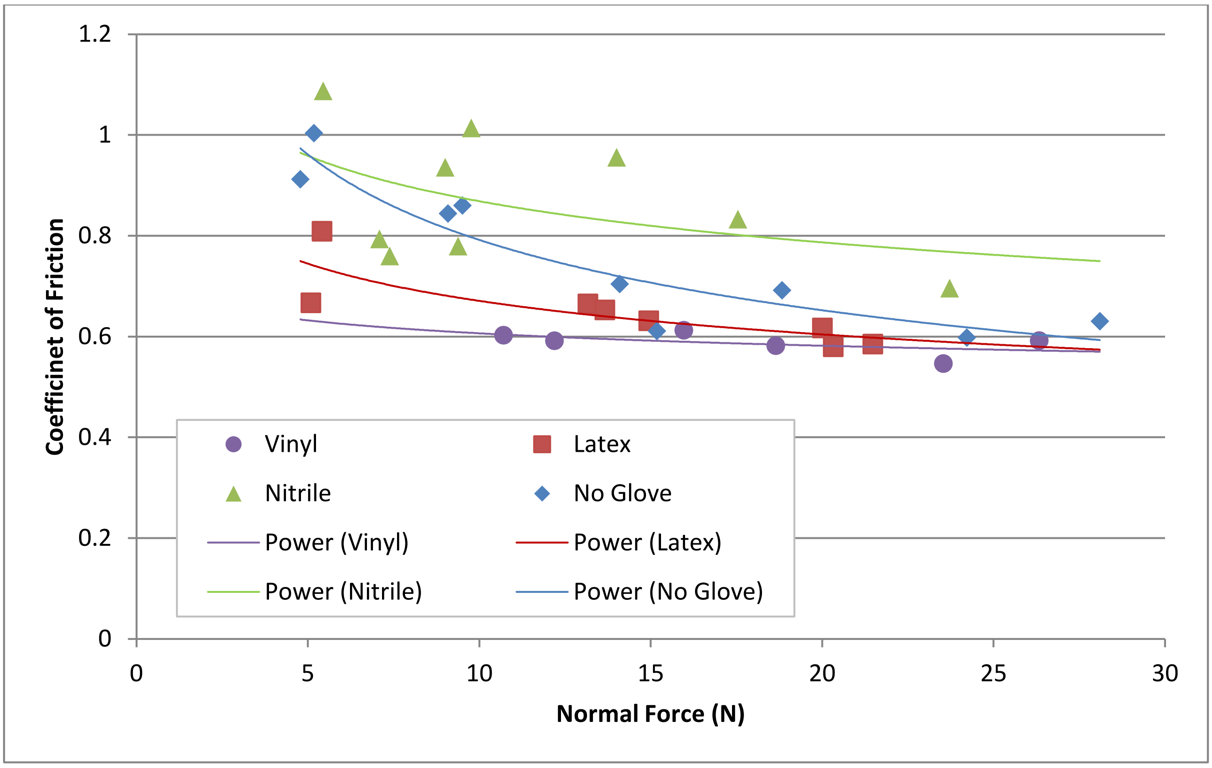


Figure 124. Wet friction results from Chadwick's [181] tests

None of the datasets deviated significantly from normality (p ≥ 0.834). Independent-samples t-tests for the dry results showed significant differences in mean between all four conditions (p = 0.000), with the latex having the highest coefficient of friction and the vinyl gloves having the lowest.

The results of the wet tests are closer together, with coefficients of friction generally lower, as expected. The nitrile gloves had the highest mean coefficient of friction, greater than that of the ungloved finger. The vinyl again had the lowest mean coefficient of friction. The results of independent t-tests between the hand conditions are shown in Table 40 and Figure 125.

Table 40. Significance of differences in mean coefficient of friction.

	Latex	Nitrile	Vinyl
No Gloves	NS (0.068)	NS (0.110)	S (0.007)
Latex		S (0.001)	NS (0.063)
Nitrile			S (0.000)

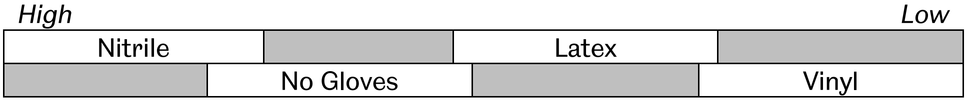


Figure 125. Schematic of significance for Chadwick's dry friction results

Discussion. The dry results are in line with what was reported by practitioners, with latex being higher than nitrile. However, the wet results are somewhat unexpected. The lowest reduction in friction when lubricated was experienced with the nitrile gloves. One possible explanation for this could be the grip pattern on the fingertips. Much like a tyre or a shoe, the grip pattern may act to disperse the water when the finger contacts the surface, reducing the lubricating effect. To make a fair assessment of the effect of material on friction, gloves identical in every other way would need to be manufactured.

Denton found the same trend in glove friction for the dry results, but found latex to be significantly higher than nitrile in the wet. He did, however, find an increase in latex friction in the wet compared to the dry condition, suggesting either that the lubrication was very low or that the results were spurious. (Previous studies [23, 120] had shown that friction between surfaces increases at high humidity compared to the dry condition; this is thought to be due to the formation of liquid bridges which require extra energy to shear. Of course, when the surface is fully wetted, lubrication effects become more significant and the coefficient of friction reduces [25].)

Evaluation of the test. The finger friction method has a number of drawbacks. Firstly, it measures dynamic friction, and, as discussed in Chapter 3, this is not representative of most medical tasks such as grasping instruments. There is also a lot of room for variation within the method, with the finger angle and sliding speed very difficult to control. An improved finger friction rig is currently in development at the University of Sheffield that allows the finger to remain static while the counterface slides under it. It is yet to be seen whether this can produce more reliable results.

8.2.2. Polyco friction angle rig

Apparatus and procedure. The friction angle rig (Figure 126) consists of two steel plates, hinged at one end. The top plate is attached to a tensometer at the other end by a cord. This allows it to be lifted at a constant rate. A circular sample of glove material is cut from the glove (normally the non-textured part such as the back of the hand) and attached to the contact surface of a weighted sample holder (150g) using double-sided tape (see Figure 127).

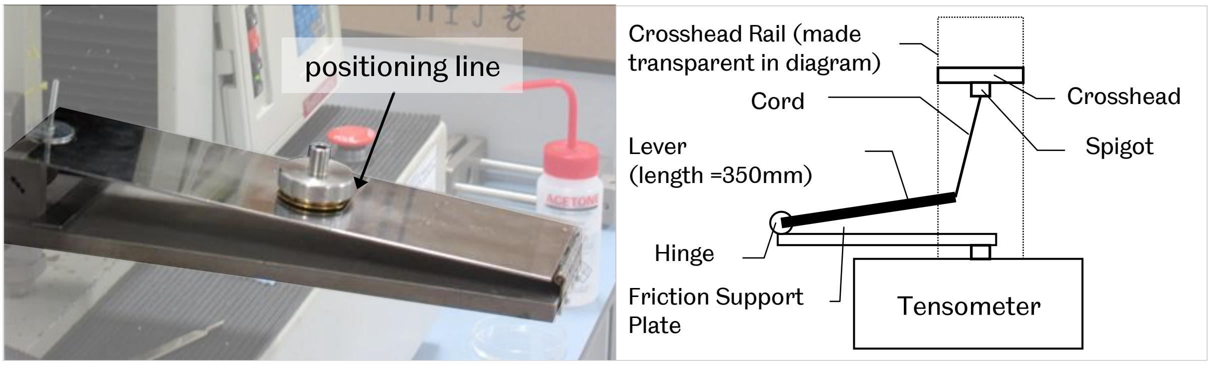


Figure 126. Polyco friction angle rig

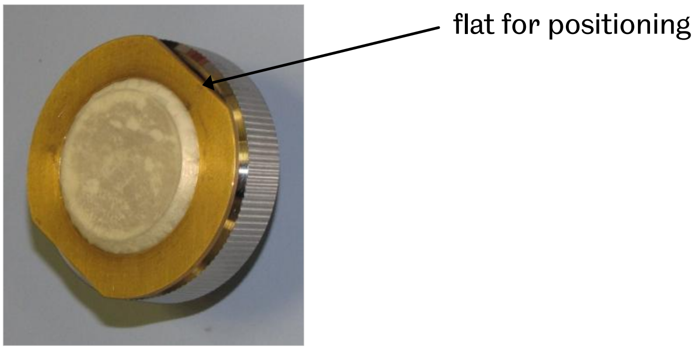


Figure 127. Polyco friction angle rig sample holder

The flat on the bottom of the sample holder is placed along the positioning line. The crossrail is then lifted at a rate of 300 mm/min until the sample holder is observed to slide down the slope. At this point, the motor is stopped and the height of the lever tip above the hinge (x, mm) is measured. The friction coefficient can then be calculated from:

$$\mu = \tan\left(\sin^{-1}\left(\frac{x}{350}\right)\right)$$

Samples were taken from eight different types of medical glove, including latex, nitrile and vinyl examination gloves; latex, polychloroprene (neoprene) and polyisoprene surgical gloves; and latex microsurgical gloves. The textured fingertip of the Indigo nitrile examination gloves was also included for comparison with the smooth sample. For each condition, three samples were taken from separate gloves, and each sample tested three times. The tests were then repeated with some of the gloves, the samples being lubricated with water or gelofusine (a gelatine-based blood plasma substitute) by placing the sample holder in a dish containing the fluid for approximately two minutes immediately prior to the test. Because of time limitations, not all gloves could be tested in all conditions. The results are shown in Figure 128.

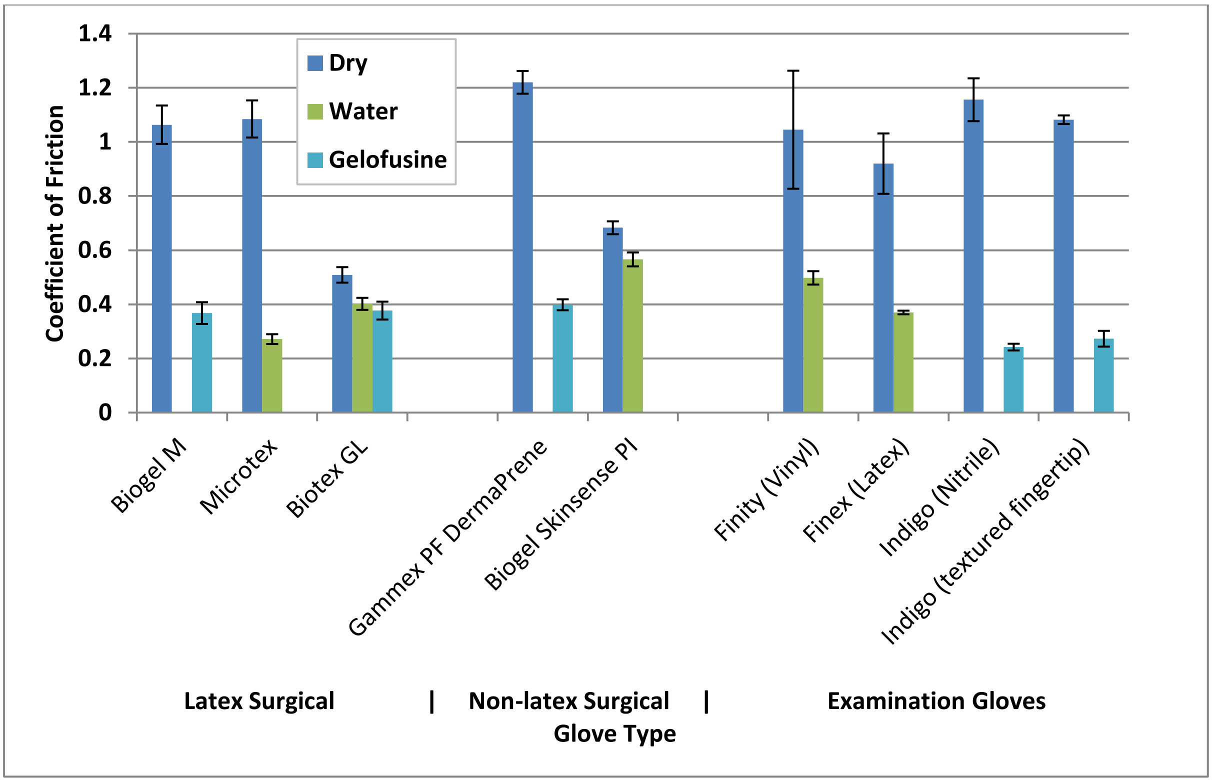


Figure 128. Polyco friction angle rig results (with 95% confidence intervals)

All datasets fitted a normal distribution (p ≥ 0.817). Independent-samples t-tests were performed on the four examination glove conditions. The results are shown in Table 41 and Figure 129.

Table 41. Significance of differences between examination gloves in Polyco friction angle test (dry)

	Nitrile	Nitrile (fingertip)	Vinyl
Latex	S (0.004)	S (0.022)	NS (0.336)
Nitrile		NS (0.117)	NS (0.371)
Nitrile (fingertip)			NS (0.749)

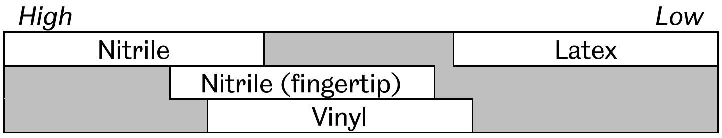


Figure 129. Schematic of significance for Polyco friction angle (dry) results

Only the latex and nitrile were significantly different from each other, with the nitrile again being higher than latex. In the water-lubricated tests, the Finity vinyl gloves had a significantly higher coefficient of friction (p = 0.000) than Finex® latex gloves.

Discussion. The results show a number of things. As expected, the lubricated tests produced lower friction than the dry tests. Surprisingly, the highest friction occurred with one of the non-latex surgical gloves (they were perceived by some practitioners to be more slippery than latex), although the other had a much lower coefficient of friction. The two microsurgical gloves were higher than the standard surgical in the dry, as expected, but not when lubricated. The textured fingertip produced a lower friction than the smooth sample from the same glove in the dry, but had higher friction when lubricated with gelofusine. This behaviour can be explained by the greater adhesion of smooth, dry surfaces than textured ones, particularly in polymers [183], while in contrast the raised bumps are less likely to be wetted than a smooth surface and so lubrication will be reduced and friction increased.

Evaluation of the test. While the results show some significant differences, there were some issues with the testing procedure. In some of the higher-friction samples, such as the Biogel® M gloves, the sample did not slip, but overturned. Gloves with this level of friction could not therefore be adequately compared. Even when overturning did not occur, the sample would often tip before slipping (see Figure 130), so that the contact area was significantly reduced. Since polymer friction is highly dependent on contact area, this will clearly affect the results. The character of the friction was also unpredictable. In some tests, the sample would appear to adhere to the surface and then suddenly “unstick” and fall, while in other tests it would start to slide very slowly (almost imperceptibly) at the critical point. Detecting or deciding the exact angle at which sliding began was therefore somewhat difficult and subjective.

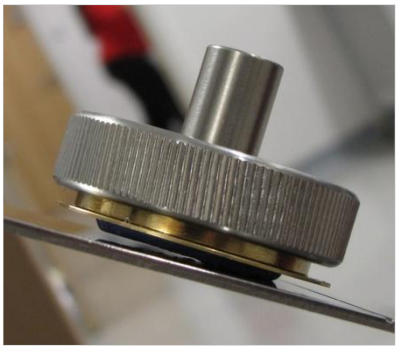


Figure 130. Tipping of Polyco friction angle sample

The fact that the glove sample is placed on a metal holder rather than a finger also means that the friction characteristics will also not be entirely realistic. With fingers, the contact area will increase with load, whereas with the metal it will remain constant. However, similar trends could be expected between the gloves.

8.2.3.Hand dynamometer

The JAMAR® hand dynamometer (Appendix A – Figure A 1) measures grip strength. The subject squeezes the two halves together as hard as possible, and the resulting increase in hydraulic pressure can be read as a force. The distance between the halves can be adjusted in five positions, and the most appropriate position for each candidate was selected based on hand size. As with Tasron's other tests, 25 participants performed the test in four conditions: ungloved, best-fit nitrile gloves, tight (one size below best-fit) and loose (one size above).

Results. The mean grip force in each of the conditions is shown in Figure 131. The highest mean grip strength was achieved in the ungloved condition.

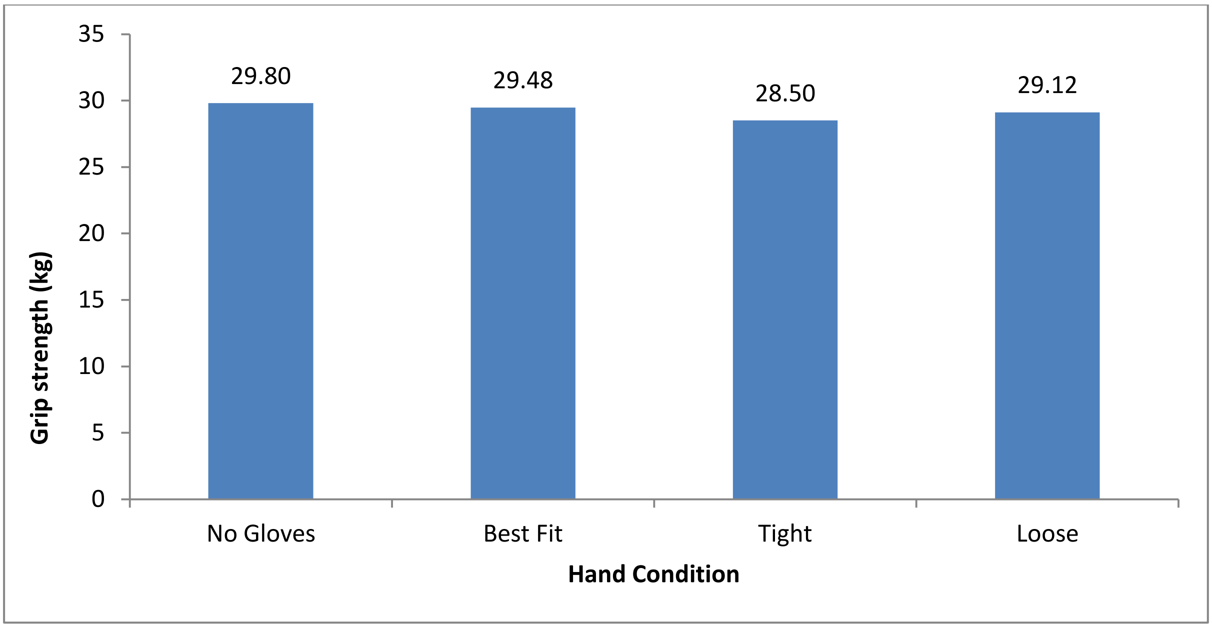


Figure 131. Mean grip strengths in Tasron's dynamometer testing

The mean difference in performance of each of the gloved conditions to the ungloved condition is shown in Figure 132.

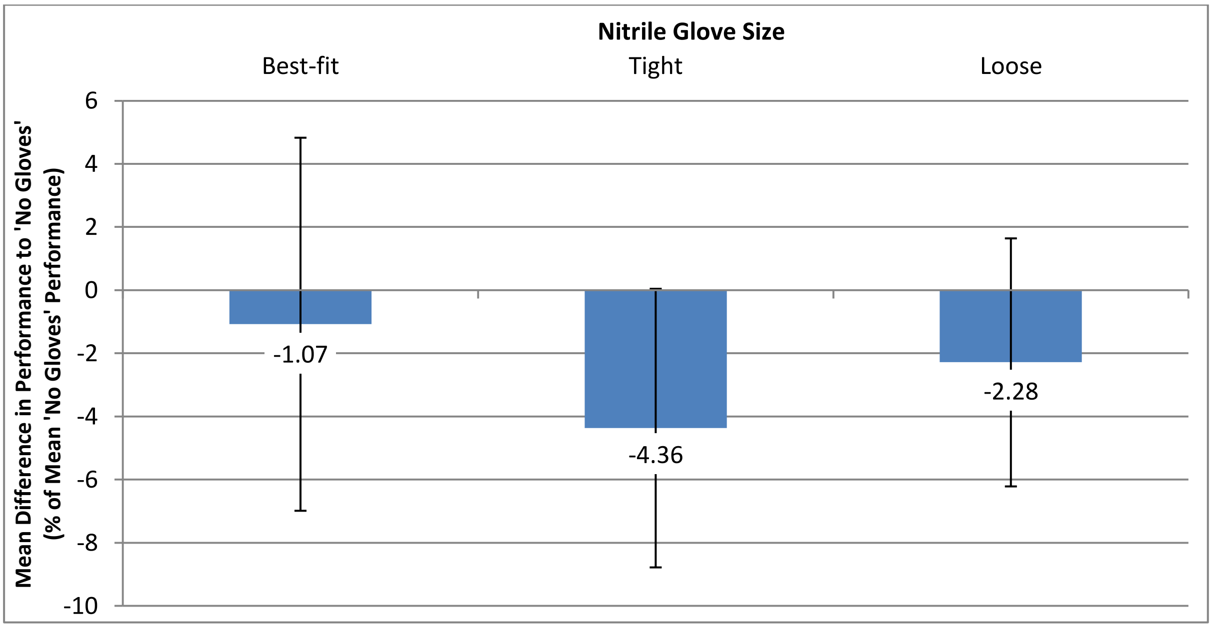


Figure 132. Mean differences in grip strength of gloved conditions to the ungloved condition (with 95% confidence intervals)

Since two of the four conditions showed significant deviation from normality, the Friedman test was used to analyse the significance of the differences. Hand condition was not found to have a significant effect on grip strength (p = 0.173).

Discussion. The results agree with previous studies (e.g. [53]) that medical gloves do not significantly reduce grip strength. While some reduction has been found with thick gloves, the thinness of the material means that it offers little resistance or absorption of energy. The tighter gloves did reduce the force by an average of 4% from bare hands, however, showing that there may be some effect from the restriction of movement caused by the tighter material. This correlates with practitioners' views that hand fatigue is worst with tight gloves. Larger scale testing might increase the significance of the result.

8.3. Pinch Grip Rig

8.3.1. Introduction

A device for measuring grip and load forces during lifting of free weights with a precision (pinch) grip was first described by Westling and Johansson in 1984 [32] and a number of variations have since been developed. The purpose of the initial study was to investigate how certain factors, such as *cutaneous sensibility* and friction, affect the regulation of grip force in precision lifting.

In its most basic form, the rig consists of a hanger with adjustable weights that is lifted by gripping two parallel plates. The weight hanger is shielded from view in order to prevent the subject from pre-empting the lifting force. Force measurement devices (load cells or strain gauges) measure the (horizontal) grip force and the vertical load on the plates during a cycle of lifting, holding and releasing of the apparatus. By measuring the load and grip forces at the point of slip during the release phase, static friction measurements can be made and safety factors calculated (the ratio of applied grip force to force required to prevent slip). The rig may also include an accelerometer and position sensor to aid in identifying the phase of the cycle (e.g. the point when slip occurs) when analysing the force readouts. A typical example of the apparatus is shown in Figure 133.

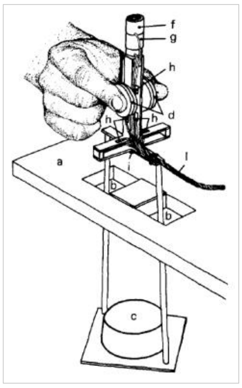


Figure 133. Pinch grip rig (reproduced from [28])

In the current study, the apparatus was to be used to show the effect of loss of tactile sensation due to gloves on the ability to grasp with an appropriate force to safely lift and hold an object. Previous work (e.g. [56]) had suggested that loss of tactile sensation due to gloves was linked to an increase in safety factor applied during grasping (i.e. an increase in the grasping force for a given slip force). It was hypothesised, therefore, that loss of tactile sensation due to gloves increases muscle fatigue when grasping surgical tools for extended periods.

It was also hoped that the equipment could be used to take static friction measurements in the releasing phase, by steadily reducing grasp force until the apparatus slipped, and measuring the grasp and frictional force at the point of slip. It was hoped that this would give a better representation of friction in tool holding than previously-used apparatus such as the Sheffield finger friction rig, which measures dynamic friction.

8.3.2. Design of the apparatus

While descriptions and schematics of previous apparatus were available, the structure of the rig had to be designed and manufactured at the University of Sheffield. A 3D CAD model of the proposed design (Figure 134) was used to produce manufacturing drawings from which bespoke parts were machined and existing components procured.

It was decided to use miniature load cells (LCM703 Universal link load cell, Omega Engineering) to measure the forces. Since the pinch force applied by the thumb and fingers would be equal and opposite once the apparatus was off the ground, it was decided that only one load cell was needed for grip measurement. However, because of frictional differences, it was possible that the load forces would be unequal, so one load cell was used for each grip pad. The main problem was then to avoid the load cells being loaded off-axis, i.e. being twisted, since this could cause false readings and possibly damage the load cells. Four rod ends (spherical joints) were used to connect the grip pads to the weight hanger, preventing twist from being transferred to the load cells, but this created another problem that the rig would not be free-standing. A central structure (marked in red) was designed that kept the pads in position while still allowing freedom of movement. This was achieved by vertical slots through which the pads were screwed into the load cell, thus allowing twist about the horizontal axis in the plane of the pads (see Figure 135).

The grip pads were designed with tapped holes to allow attachment of alternative surface materials and textures, and the entire finger pad could be replaced with, for example, one made of Perspex, through which the finger or glove could then be viewed during gripping in order to obtain more information about how slipping occurs.

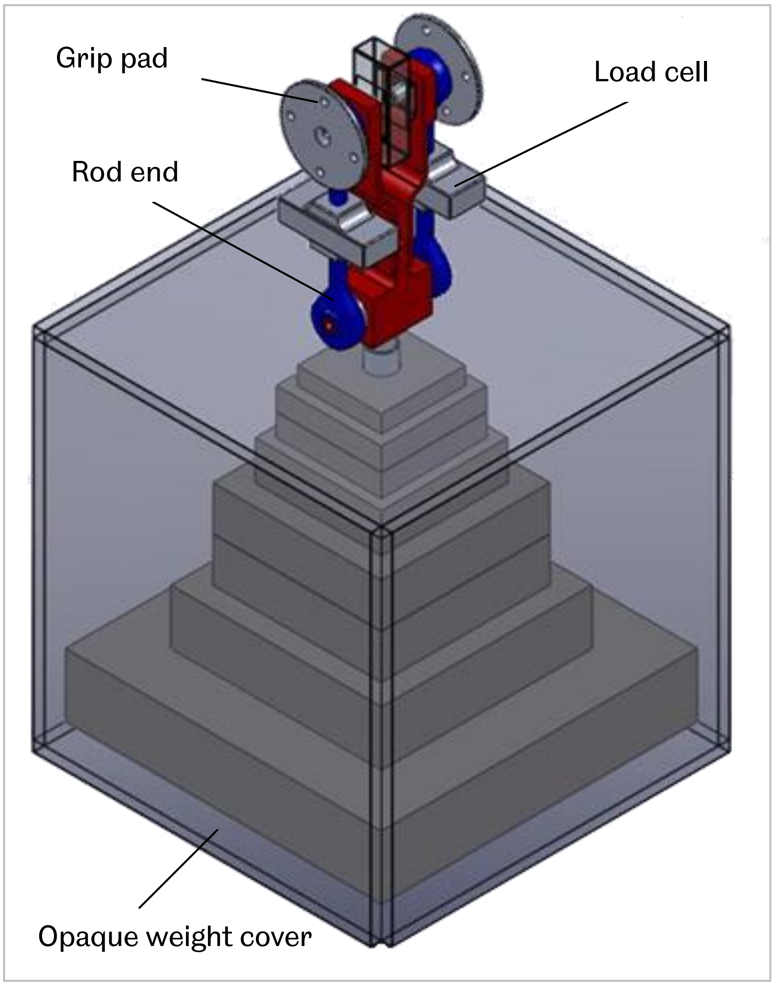


Figure 134. 3D CAD model of prototype pinch grip rig

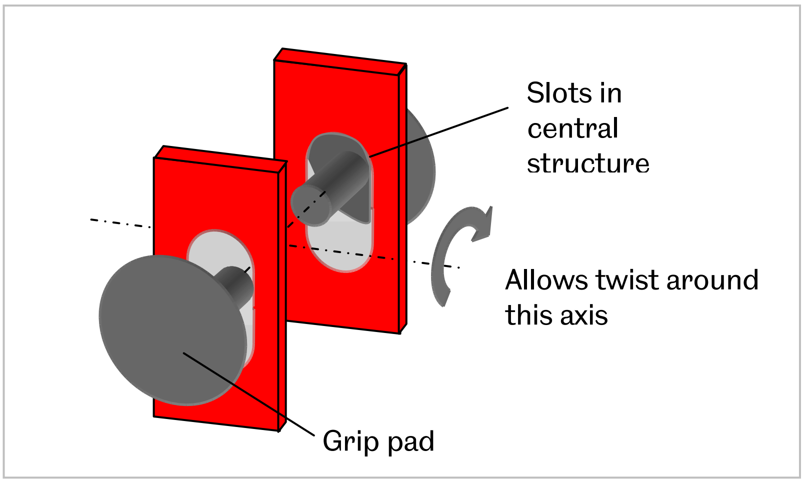


Figure 135. Schematic of pinch grip rig design

The masses were placed on a custom built hanger, and hidden with a thin metal box that could be removed when mass adjustment was needed. The base of the hanger was replaced with Perspex after it was found to be too heavy.

The load cell capacities were selected based on available grip strength data [184] and previous glove friction measurements (see Section 8.2). The grip force load cell had a range of ±25kg, while the vertical load cells had a range of ±10kg, allowing a maximum of 20kg to be lifted. An accelerometer was initially attached to the rig in order to detect the vibrations that occur when the surfaces begin to slip, but, despite trying a number of available models, the sensitivity was not sufficient to detect vibrations of such small amplitude. It was therefore necessary to measure the point of slip from the load force data, being the point at which it began to drop off from a steady value. This approach has been used previously (e.g. [32]) and corresponds well with the positional data (see Figure 136).

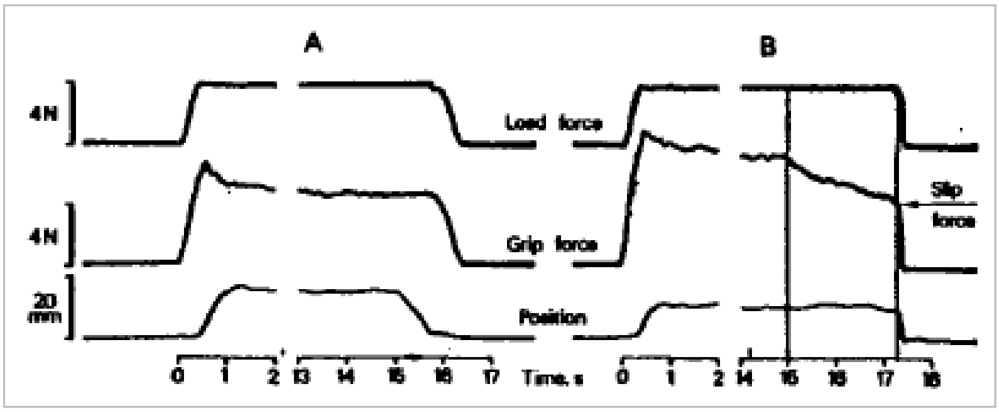


Figure 136. Load force, grip force and vertical position shown as a function of time for two different kinds of lifting trials. (A) sample trial with lifting and replacing of the object in an ordinary manner. (B) sample trial with dropping of the object due to a slow voluntary spacing of the fingers at the end of the trial. (reproduced from [32])

A routine was developed in LabVIEW that recorded the loads at a sampling rate of 2000Hz. The results were then processed in MATLAB to produce force-time plots for each test, from which the data could be extracted. The assembled apparatus is shown in Figure 137.

Figure 137. Finished pinch grip rig

8.3.3. Experimental design

Two subjects participated in the trials; both were healthy adult males. The tests were carried out using the Finex, Indigo and Finity examination gloves and ungloved (one subject did not complete the Finity test because of time restrictions). The order of hand conditions was randomised for each subject. The subject selected the best-fitting size for each glove. Five mass levels were selected for the test, giving the apparatus total weights of 10, 11, 15, 17 and 27N. The subject performed five tests in each of the hand conditions, one at each weight level, with the order of the weights randomised. The first subject also performed a further ten tests in the ungloved condition in order to determine the repeatability of the test.

Procedure. The procedure for each test was as follows: the selected set of masses was attached, the apparatus was placed on a soft foam pad, and the loads were zeroed. The data acquisition was started, and the subject was asked to lift the apparatus off the foam pad using the thumb and first two fingers of the dominant hand, and then to hold the apparatus steady for approximately five seconds. They were then told to slowly release the apparatus until it dropped onto the foam mat. Once the apparatus had fallen, the data acquisition was stopped.

8.3.4. Results

A typical force-time plot for the pinch grip test is shown in Figure 138. It can be seen that the pinch force gradually increases (in the negative direction, since it is compressive), almost in parallel with the lift force, which increases up to the weight of the rig and then levels out. This is the holding phase. The pinch force often has a spike to a maximum before reducing to a steady value as the subject determines the force required for holding. The subject also sometimes adjusted their grip force part way through the holding phase. After the holding phase, a steady decrease in grip force occurs as the subject releases the apparatus, until slip occurs on one of the pads, at which point the rig begins to twist and then falls as friction is overcome on both sides.

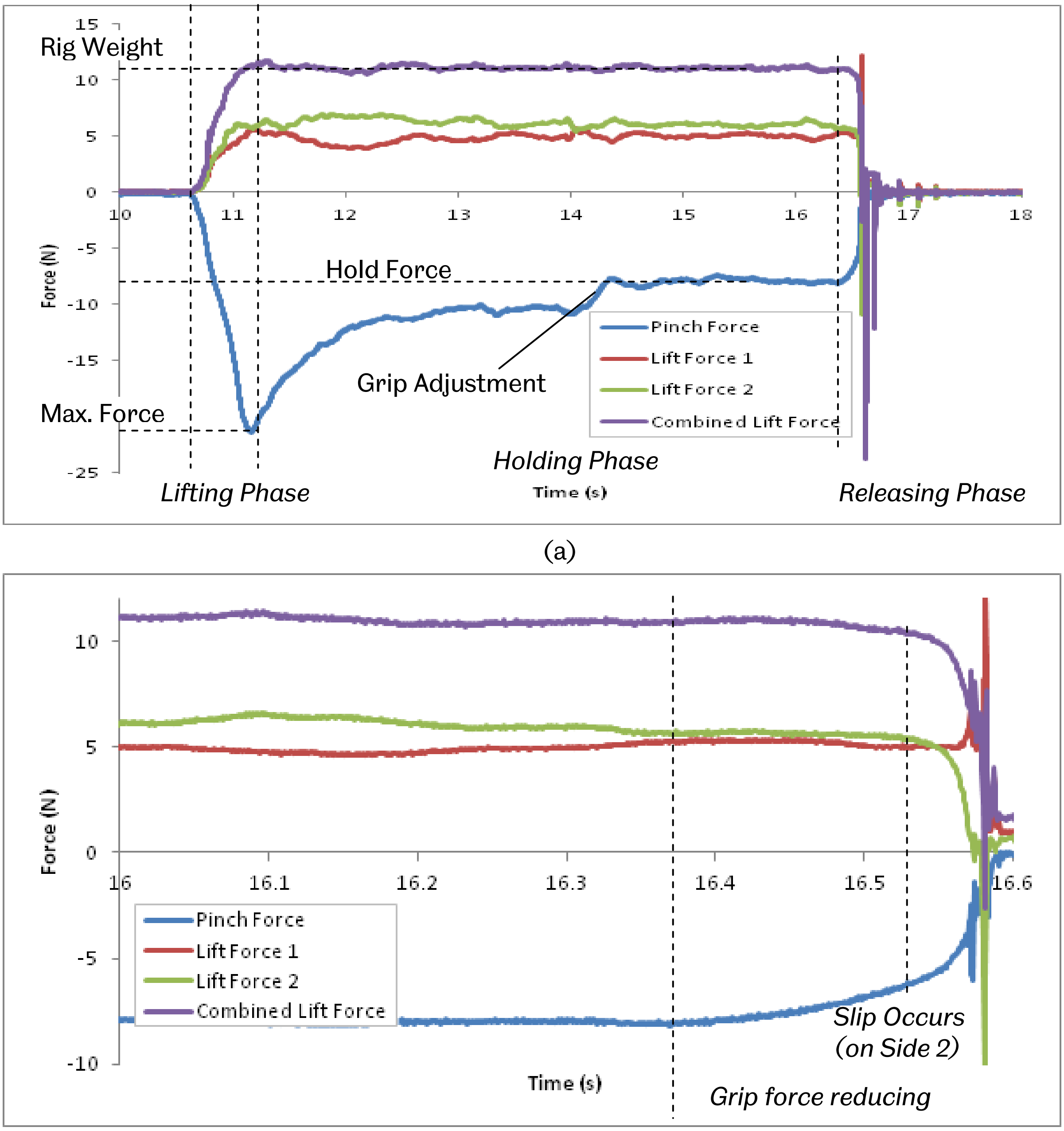


Figure 138. Typical force-time trace for the pinch grip test (a) whole test and (b) release phase

The mean coefficients of friction for latex, nitrile and vinyl examination gloves and in the ungloved condition, calculated at the point of slip, are shown in Figure 139.

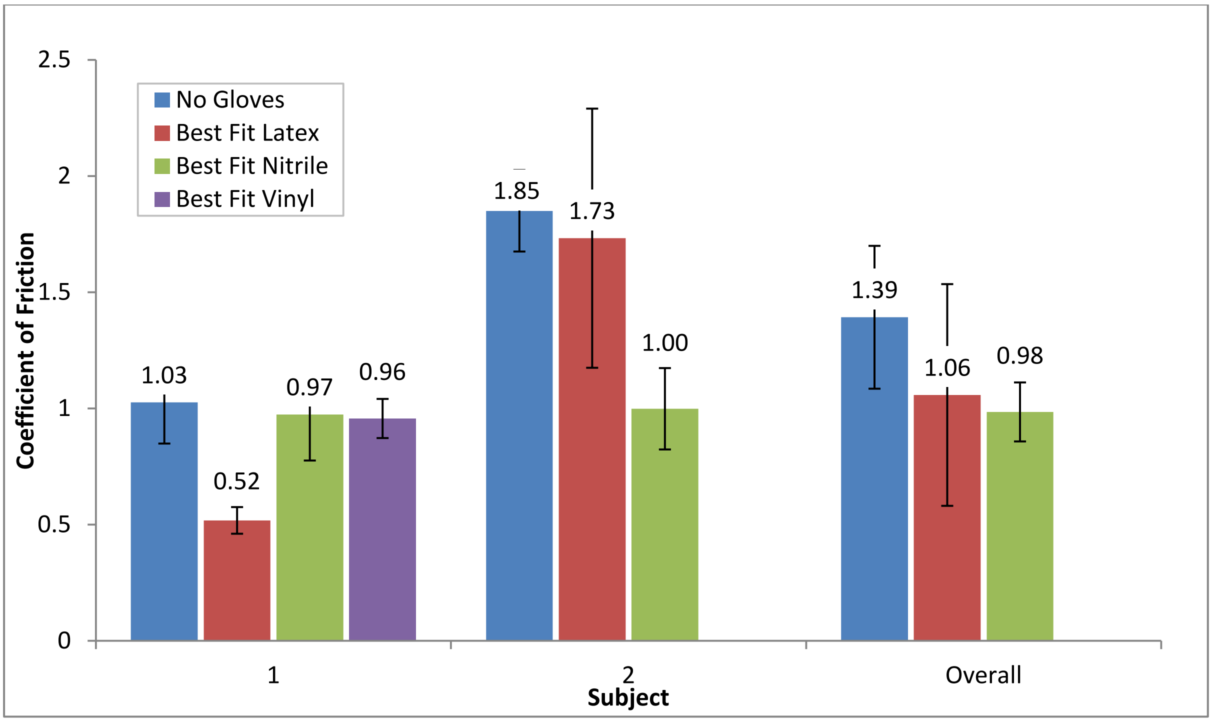


Figure 139. Mean coefficient of friction in four hand conditions for two subjects in the pinch grip test (with 95% confidence intervals)

The mean ratio of maximum force, holding force and slip force to weight with latex and nitrile gloves and ungloved are shown in Figure 140.

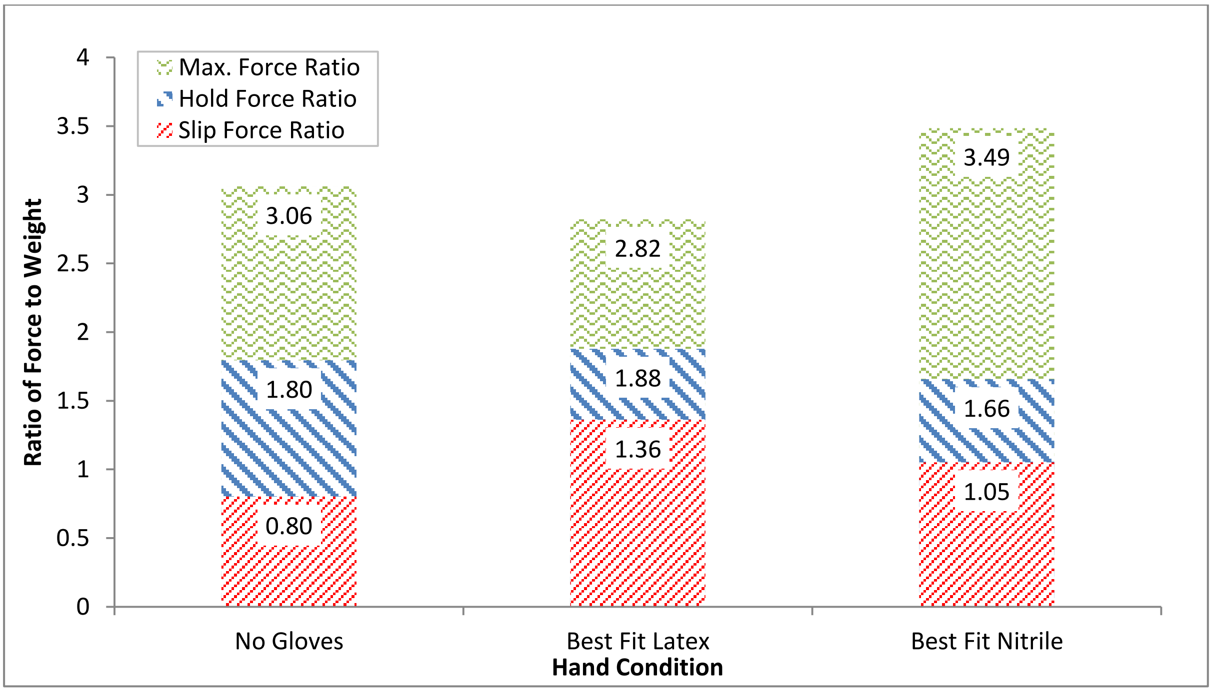


Figure 140. Mean ratio of maximum, hold and slip force to weight for three hand conditions (n = 2)

When the relationship between normal (pinch) force at slip and coefficient of friction is considered (Figure 141), a similar relationship is found to that shown in the Sheffield finger friction results for a similar range of normal forces – coefficient of friction decreases slightly with increasing normal force, flattening out at higher forces.

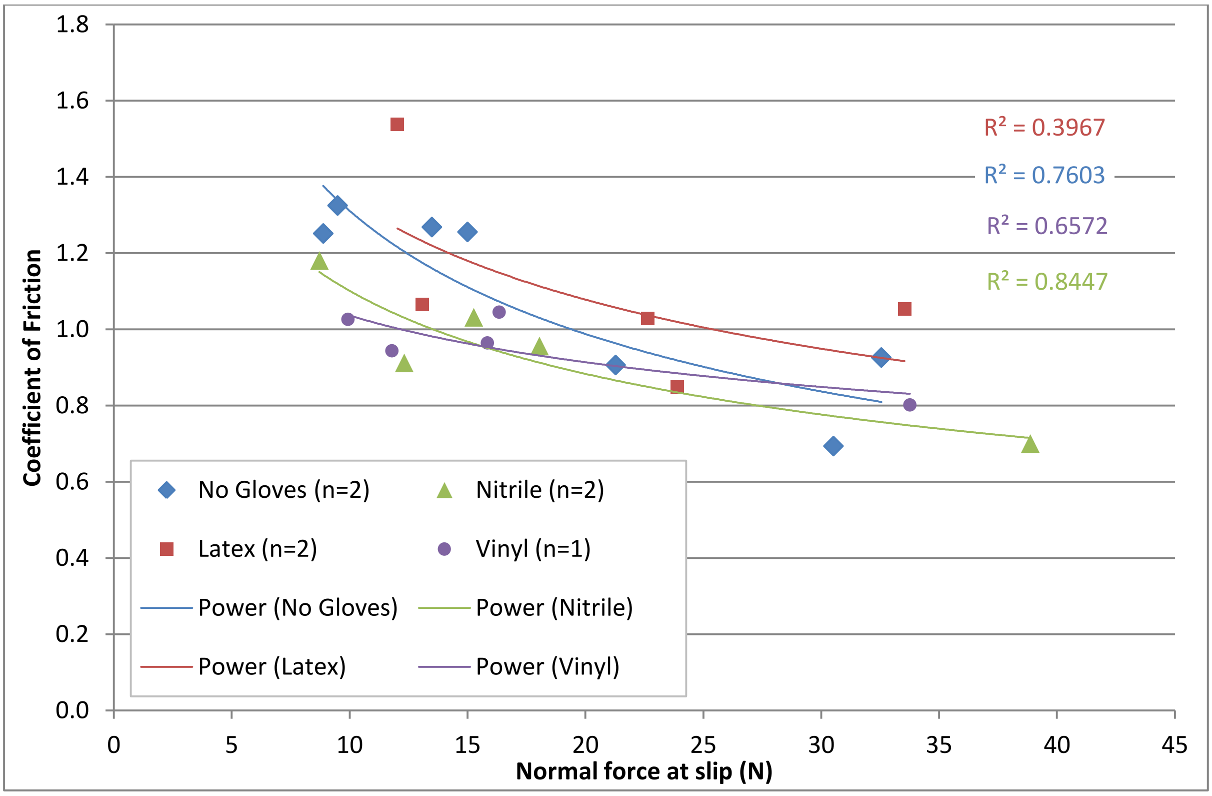
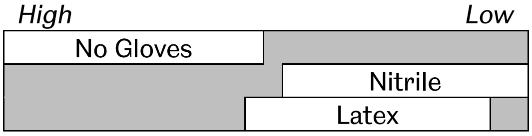


Figure 141. Coefficient of Friction vs. Normal Force for four hand conditions in the pinch grip test

Statistical analysis. Independent-samples t-tests between hand conditions were performed on the friction results. (Paired tests were not used due to the large variation between subjects.) Only one dataset showed a significant deviation from normality ($p = 0.050$), so t-tests were felt to be appropriate. The results are shown in Table 42 and Figure 142.

Table 42. Significance of differences in coefficient of friction in pinch grip testing

	Latex	Nitrile	Vinyl (participant 1 only)
No Gloves	NS (0.304)	S (0.023)	S (0.014)
Latex		NS (0.609)	NS (0.523)
Nitrile			NS (0.768)



(Only results obtained with both participants are included)
Figure 142. Schematic of significance for pinch grip testing

T-tests on the hold force and maximum force ratios for each hand condition showed that, while there were significant differences in coefficient of friction between hand conditions, there were no significant differences in the mean hold force ratio or mean maximum force ratio ($p \geq 0.177$ in all t-tests, see Table 43 and Table 44).

Table 43. Significance of differences in Hold Force Ratio between hand conditions

	Latex	Nitrile
No Gloves	NS (0.959)	NS (0.245)
Latex		NS (0.507)

Table 44. Significance of differences in Maximum Force Ratio between hand conditions

	Latex	Nitrile
No Gloves	NS (0.530)	NS (0.177)
Latex		NS (0.187)

In other words, for any given weight, the maximum pinch force and the steady holding pinch force were constant across hand conditions, regardless of friction, so that the hold safety factor actually increased with the coefficient of friction. Analysis of the Pearson correlation between calculated coefficient of friction and holding safety factor for all tests confirmed this (Correlation Coefficient = 0.654, p = 0.000).

The relationship can be seen in Figure 143. This conflicts with Johansson and Westling's [28] findings that subjects adapt grip forces to frictional conditions to give a fairly constant safety factor.

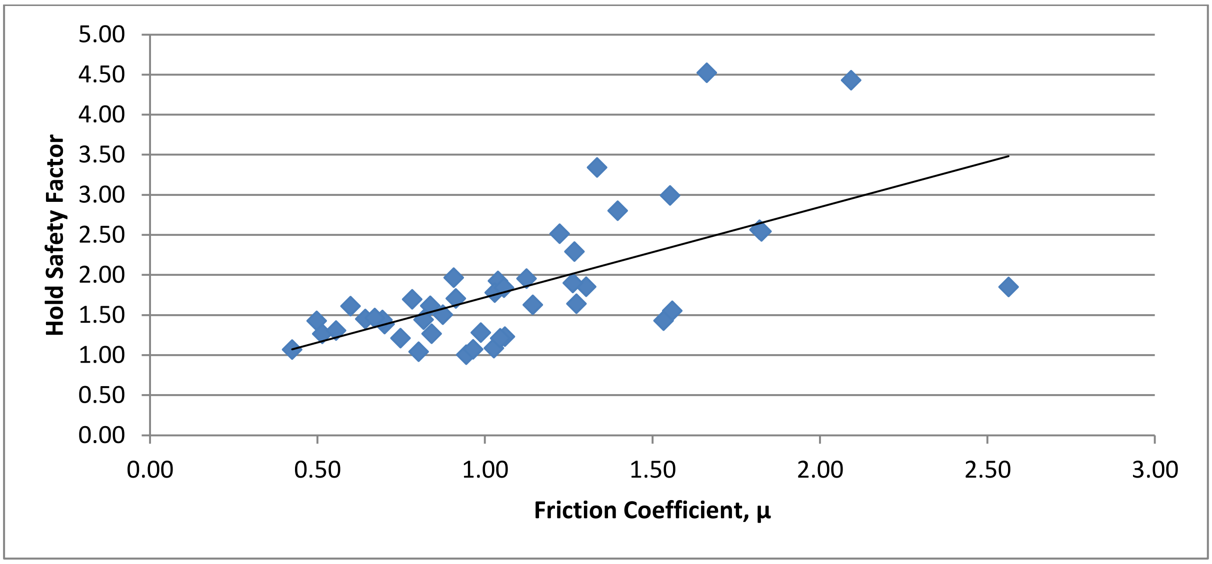


Figure 143. Safety Factor in holding phase against coefficient of friction for all 44 pinch grip tests

Pearson correlations between maximum and hold force ratios and safety factors, coefficients of friction and weights for all the hand conditions were examined, but no other clear trends emerged.

8.3.5. Discussion

The results vary considerably between subjects, so testing with a much larger population is required before any firm conclusions can be drawn about the effects of gloves on friction in grasping. Variation in skin friction between candidates and even between tests could be expected as skin moisture content can vary over time, and the density of sweat gland distribution in the skin will vary between candidates. However, it was expected that gloved scores would be similar, whereas in testing the coefficient of friction of latex gloves for the first subject was 30% of that for the second subject. It may be that the slip is first occurring sometimes between glove and counter-surface and sometimes between finger and glove, giving very different values and depending on the candidate's finger properties. Further investigation, perhaps with video recording through Perspex pads as proposed, is needed to characterise the mechanism of slip. Similarly, there is not enough evidence to draw conclusions about the relationship between tactile sensitivity and grasp forces.

While the method produces a large amount of data, the accuracy of some of the readings, particularly the static friction measurements, is doubtful. The large variations within and between subjects suggests that the method of detection of slip (using only the force readings) is not very effective and needs to be supplemented with accurate position or vibration data.

The apparatus would also be more effective in determining friction in medical practice if real surgical tools and grasps were used. The distance between the pads, necessitated by the load cell (see Figure 137), meant that the grasp was awkward and unnatural. Modification of tools with smaller-scale devices such as strain gauges could achieve the desired effect. Another approach is to use an artificial hand, from which measurements could be taken on unmodified instruments. The development of such a device is detailed in the following section.

8.4. Anthropomorphic Device for Simulating Hand-Object Interactions (ADSHOI)

8.4.1. Background

Basic attempts were made to measure friction in surgical tool grasping by attaching a scalpel handle to a force meter and pulling until the hand slipped off (see Figure 144). Denton [182] used the rig with dry and lubricated gloves and bare hands and found some differences in the peak force at slip. However, this approach does not give a value of friction, only a maximum shear force, and makes results dependent on the grip strength of the subject. It was also not a realistic simulation of the grasp forces used in surgery. One solution would have been to modify the instruments so that grasp (normal) force on them could be measured, but there were a number of issues with that, including the cost and time involved in modifying the instruments and the limitation to one or two instruments.

Figure 144. Scalpel rig prototype

An alternative was to control the grasp force by clamping the hand. Experiments had previously been carried out at BM Polyco Ltd in which the instrument was held in a universal testing machine (UTM). The handle was grasped by the operator and it was attempted to clamp the hand with a known normal force. A steadily-increasing tangential force was applied by the UTM until the scalpel slid from the grasp, and the maximum tangential force was recorded.

However, there are a number of problems with this method: the hand used (and therefore the test subject) must be the same each time, and in the same condition; it is very difficult to apply a known force through a hand which contains a neuromuscular system that will respond involuntarily to slip by tightening its grip; and there are ethical and safety issues in clamping people's hands.

The solution proposed was to create an artificial hand that could safely be clamped and would provide repeatable and reliable results indefinitely. The issue was then to create a hand that mimicked real frictional and deformation properties so as to give a realistic simulation of hand-object interaction.

Shao et al. [118] created a number of artificial fingertip models for human feeling studies, with the intention of creating realistic friction and softness properties. They used both solid silicone and multi-layered models, consisting of three layers: the outer skin was simulated by an encapsulated silicone, coated in acrylic to reduce friction; the soft tissue was simulated by a mixture of silicone gel base and elastomer; and the bone was simulated using a hard acrylic. An example can be seen in Figure 145. They found that as the softness of the artificial fingertip neared the softness of a real fingertip, so the frictional properties converged.

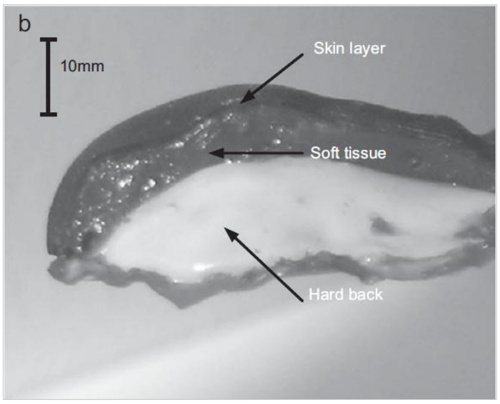


Figure 145. Artificial fingertip (reproduced from [118])

It was proposed to incorporate the fingertips into a model of a hand, so that medical gloves could be pulled over it, and would deform and move in a realistic way.

8.4.2.Initial prototype

A prototype was made using existing hand and finger moulds. The hand was made from flexible foam and was articulated with armature wire in each digit. The fingertips were made to the same specifications and using the same moulds as the ones Shao et al. used. The prototype is shown in Figure 146.

Figure 146. Artificial hand prototype

There were a number of issues with the prototype. Putting a glove on the hand was very difficult, due to the high friction coefficient of the foam, even with the polymer gel-lined surgical gloves. This is made more difficult because, unlike a real hand, the fingers cannot easily move to assist the donning. In terms of the realism of the apparatus, the main problems were that the thumb and first two fingers of the foam hand were cut off at the *distal interphalangeal* (DIP) *joint*, so that there was no material where the fingernails should be, and the fingertips and hand did not match. These issues meant that the gloves did not sit in a natural way over the fingers, and were slack at the fingertips.

8.4.3.Final design

A new, improved design was proposed. The improvements included: making the hand from acrylic-coated silicone instead of foam, which made it more slippery; making the entire *distal phalanx* detachable, with the back made from a hard acrylic, so that clamps or similar can be attached, and the tips being layered, as before; making the transition between fingertip, *distal phalanx* back and hand smooth; moulding both the *distal phalanges* and the rest of the hand from the same real hand, moulded in the pinching position to avoid overstretching of the material.

New moulds were made for the hand and the fingertips, using a hand that had been measured and found to be statistically average (being between the 25th and 75th percentiles for 11 different measurements). The moulds were initially made from silicone and encased in plaster to provide stiffness (see Figure 147), before being inverted twice, using rubber and foam, to provide the master moulds.

Figure 147. Creation of the ADSHOI

The exact proportions of silicone gel and elastomer in the fingertips need to be precisely controlled in order to get the right compliance, and due to changes in the silicone supplied, the fingertips felt softer than the previous mouldings. However, creation of permanent moulds means that adjustment of the mix is fairly easy and could be explored in future development of the device.

8.4.4. Stiffness testing

The stiffness testing apparatus detailed in Section 7.6.5 was used to test the artificial fingertips from both prototypes against real fingertips from the hand used for the moulding (see Figure 148). The results are shown in Figure 149.

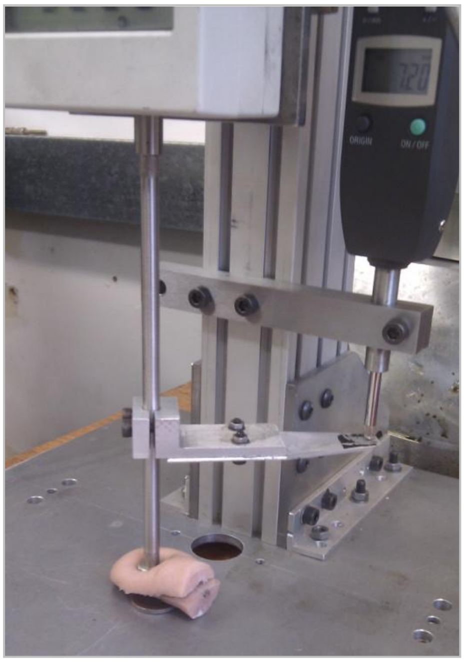


Figure 148. Stiffness testing of artificial fingertip

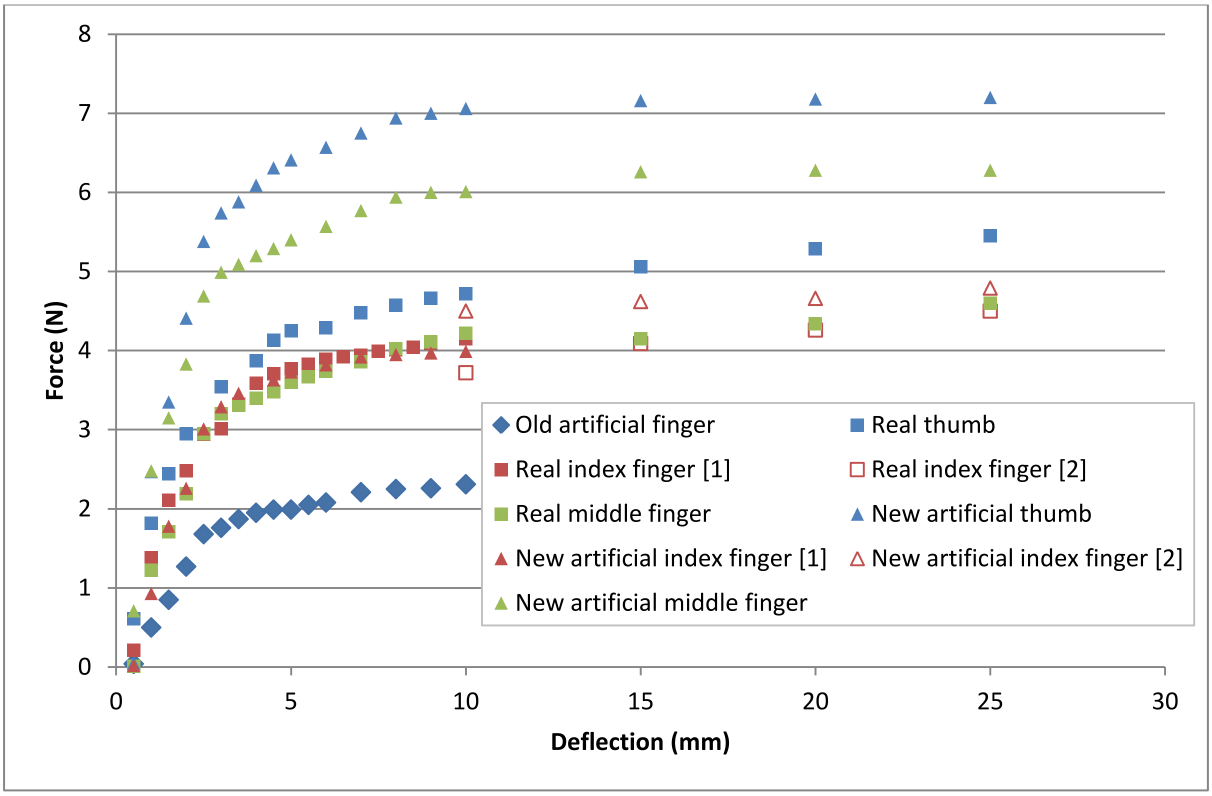


Figure 149. Force-deflection curves for real and artificial fingertips

The original artificial finger was actually much stiffer than the real fingertips, while the thumb and middle finger of the new hand were much softer. The stiffness of the new artificial index finger was very close to that of the real finger. However, some calibration of the moulding is clearly needed to obtain realistic stiffness and frictional properties for all three digits.

8.4.5.Rig design

The eventual aim of the anthropomorphic device development is to produce a hand that can be moved into any position and a force applied and measured on any tool or object. However, because of time limitations within the project, it was decided to limit the development to validation of the frictional properties of the hand with the pinch grip rig. This allowed force measurement external to the hand, and required only one grasp position. A rig was designed that held the hand in place and applied a clamping force to the thumb and to the index and middle fingertips collinearly. The height of the rig was such that the pinch grip apparatus was suspended just above the table when held in the device. The apparatus is shown in Figure 150.

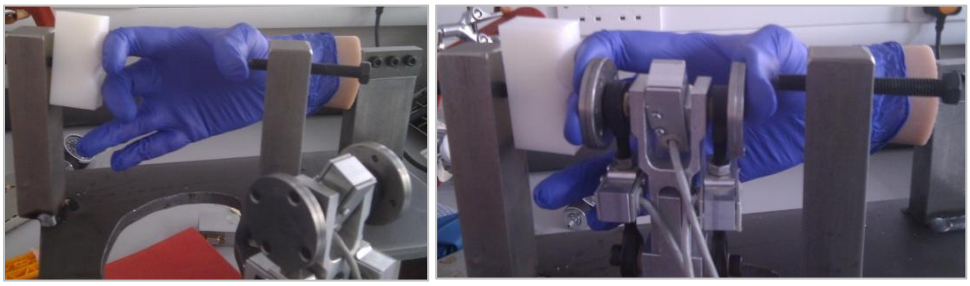


Figure 150. Anthropomorphic device with pinch grip testing apparatus

8.4.6. Experimental design

The experimental procedure was similar to that for the human pinch grip rig testing (Section 8.3.3). After starting the data acquisition, the pinch grip apparatus was placed in between the thumb and fingers, the screws tightened until the weight of the apparatus was held fully in the device. The screws were then slowly loosened in increments until the pinch grip apparatus began to slide, pausing to check at each increment before unscrewing further.

The three types of examination glove (Finex®, Indigo and Finity) were used for the testing. Because of the softness of the fingertips, they tended to shear and peel away, so lower loads were used than for the human testing, and the hand was not tested ungloved (the gloves provided some support to prevent the skin layer peeling off). All the gloves used were Medium, which was the best-fitting size for the subject whose hand was used for the mould. Each glove was tested at six weight levels between 3 and 10 N, with one test at each level.

8.4.7.Results

The force-time graph for a typical test is shown in Figure 151. It can be seen that the pinch force reduces in discrete steps (as the screws are loosened) before falling off as the pinch grip apparatus begins to slide.

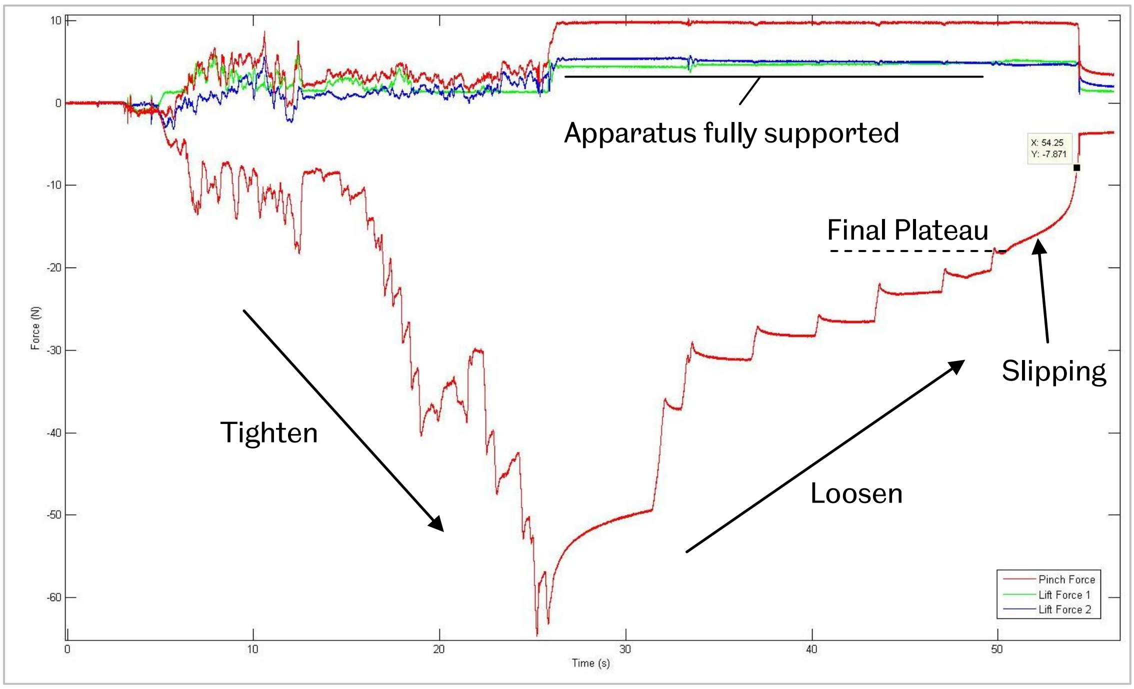


Figure 151. Typical force-time graph for anthropomorphic device glove testing (combined lift force shown in red at top of image)

As with the human testing, the weight was calculated from the flat portion of the combined lift force trace. The normal force at slip was then calculated from the small plateau immediately after the final turn of the screw. It was felt that using the point where the lift force began to decrease was an unreliable indicator of slip (as shown in the human testing). The difference may be due to the fact that, even though the limit of friction has been reached and static friction is overcome, the apparatus begins to slide at a fairly constant rate, which causes the lift force to remain fairly constant. Only at the point where the apparatus moves out of the grasp does it accelerate and a drop in lift force occurs. Taking the final plateau as the normal force at slip provided more consistent friction results across each hand condition. The mean coefficient of friction for each of the three glove types is shown in Figure 152, and the friction-normal force curves are shown in Figure 153.

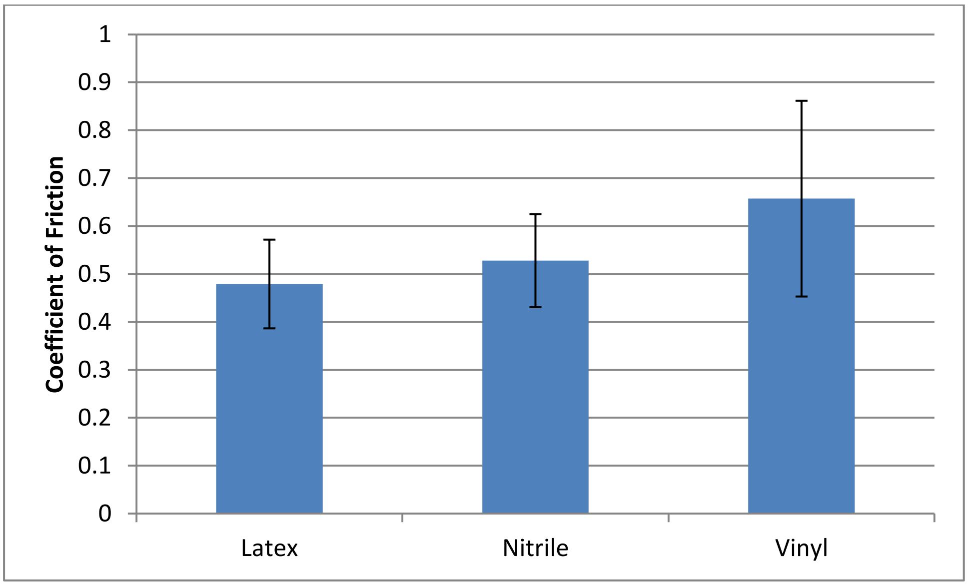


Figure 152. Mean coefficient of friction in the anthropomorphic device testing for three types of examination glove (with 95% confidence intervals)

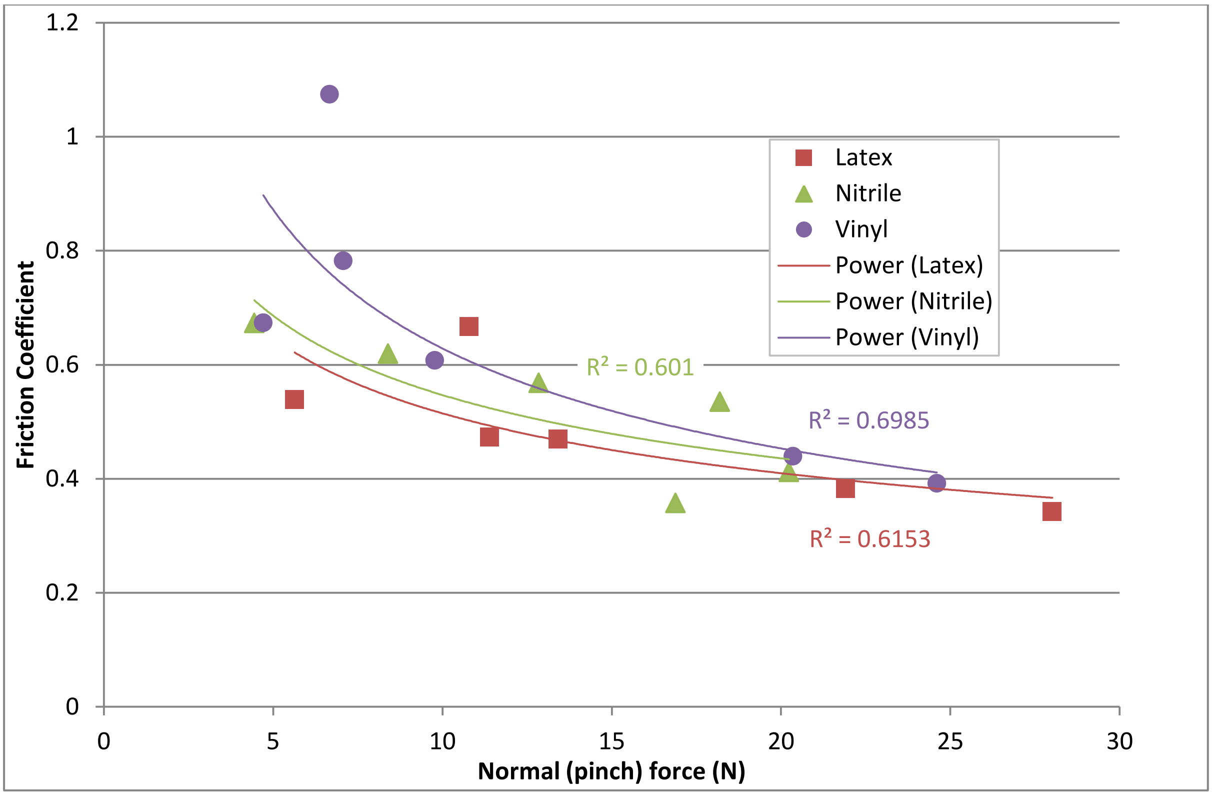


Figure 153. Friction vs. normal force for three examination gloves in anthropomorphic device testing

It can be seen that the vinyl glove had the highest mean coefficient of friction with steel, and the latex had the lowest. However, there was greater variability in the vinyl results.

Statistical analysis. None of the three datasets deviated significantly from a normal distribution ($p \geq 0.719$). The results of paired t-tests between glove types across the six weight levels are shown in Table 45 and Figure 154. The vinyl glove had a significantly higher coefficient of friction than the latex.

Table 45. Significance of differences in coefficient of friction for examination gloves in the anthropomorphic device pinch grip testing

	Nitrile	Vinyl
Latex	NS (0.404)	S (0.033)
Nitrile		NS (0.234)

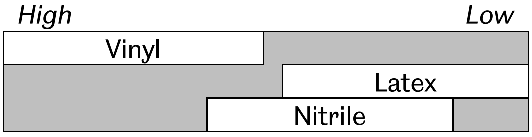


Figure 154. Schematic of significance for differences in coefficient of friction in the anthropomorphic device pinch grip testing

8.4.8. Discussion

The coefficients of friction were much lower than those found in the human pinch grip testing, even though the average weight was much lower. This could be expected since the normal force at slip was measured with a different method (using the final plateau) that gave a much higher value in some cases than at the point where the lift force dropped off.

There were some strange results with the vinyl, with the pinch grip apparatus slipping at a slightly higher pinch force with a 5.5N weight than with a 7.2N weight. Observation of the testing showed that slipping did not happen in a consistent way. As with the pinch grip human testing, the apparatus generally slipped on one side first, but as with the Polyco friction angle testing, it sometimes slipped suddenly, and at other times slid slowly and stopped in a different position before finally falling with further loosening. The elastic nature of the fingertips meant that the pinch force changed as the apparatus moved position. This could be a realistic representation of what happens in human grasping, but makes consistent friction measurement difficult.

8.5. Discussion

Four methods were used to measure the coefficient of friction of examination gloves with steel in the dry. Two of them were also tested in wet conditions. A comparison of the significance of differences found between latex, nitrile and vinyl gloves with each method are shown in Figure 155 and Figure 156 for dry and wet conditions respectively.

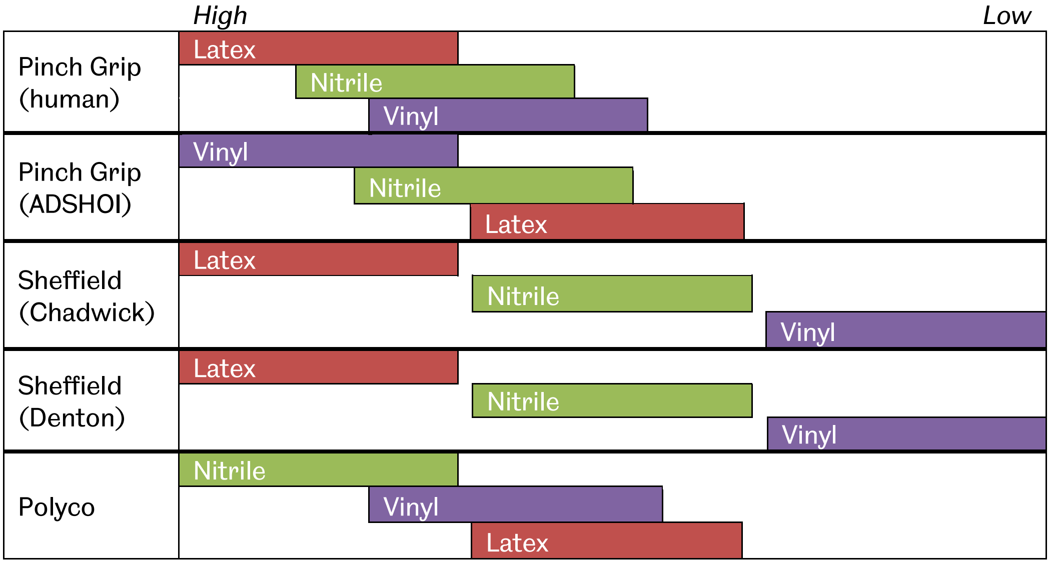


Figure 155. Schematic of significance for all dry friction tests

The Sheffield finger friction rig produces the biggest differences in dry friction between the gloves and the ranking of the gloves was consistent between experiments. However, the test measures dynamic friction, while most medical applications require static grasping of instruments. The wet results are less consistent, although the variation in method of lubrication (placing in a container of water and placing under a tap) may have produced different amounts of lubrication. The method is also susceptible to changes in sliding speed and angle of attack that may affect the results. Furthermore, Denton found issues with the measurement equipment where the battery-powered load cell amplifier tended to change the recorded force values over time. Improved apparatus currently in development at the University of Sheffield uses more reliable data acquisition equipment and moves a surface over a static finger at a constant speed. This should produce more consistent results.

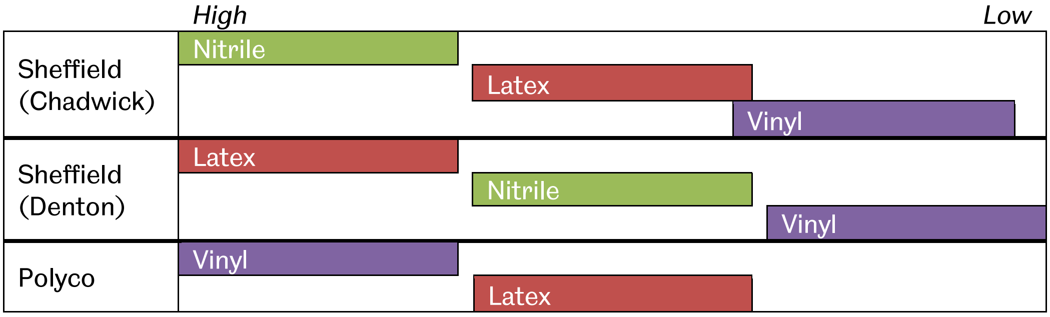


Figure 156. Schematic of significance for all wet friction tests

The Polyco rig produced some significant differences and fairly low variance in both the dry and the wet, but also had a number of issues with the testing procedure in terms of detecting the actual point of slip. Video equipment could increase the accuracy. However, the method is probably the least realistic of the four, since there is no simulation of the elastic properties of the fingertip, the surface is entirely flat and the load is much lower (1.5N) than in most grasping. This could account for the very different ranking between the gloves compared to three of the other tests. The equipment could be modified to increase the weight and to replace the flat metal surface with a polymer such as silicone, shaped more like a fingertip.

The pinch grip rig was tested both with human grasping and with an artificial hand. The variation between the human subjects was found to be large, and the results did not correlate at all with the artificial hand testing. The human testing is the best approximation of grasping forces in medical practice, although the size and shape of the rig made the grasp somewhat unnatural. It may be that the inconsistency in the results is a genuine representation of real conditions, since grasps are constantly being adjusted, and the glove material will tend to wrinkle and stretch, changing the frictional characteristics. However, the method of detection of slip still needs to be improved for both tests, perhaps using accelerometers and accurate position sensors to determine the start of slipping. The elastic properties of the anthropomorphic device also need to be optimised to best simulate real fingertips and the robustness of the fingertips needs to be addressed so that they can be used reliably at higher loads for longer periods of time before needing replacement. Further development of measurement and actuation equipment is needed before the device can be used on real tools.

None of the methods gives a definitive answer to the question of which glove has the highest friction in any given situation, and there is certainly no consensus on the value or range of values of the coefficient of friction. The differences in measured coefficient of friction between methods and variation with normal force are shown in Figure 158 and Figure 159 for dry and wet conditions respectively (see Figure 157 for an explanation of the graphs).

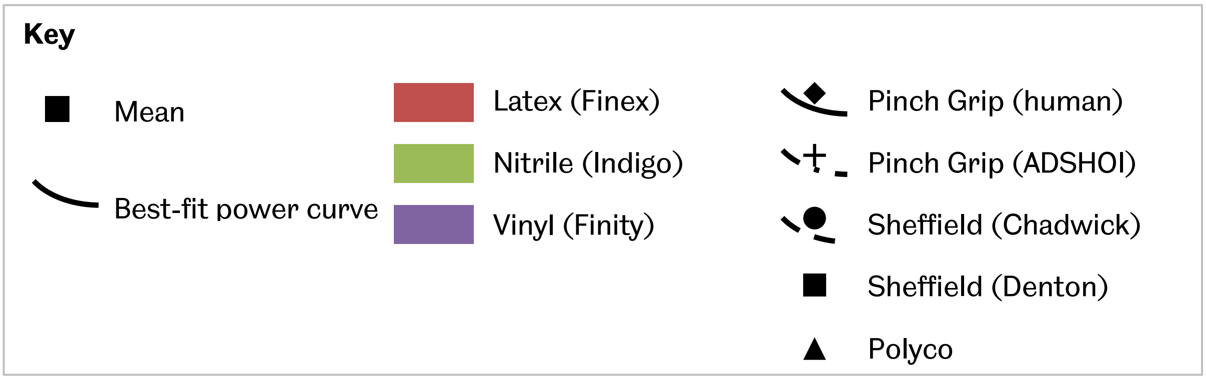


Figure 157. Key for Figure 158 and Figure 159

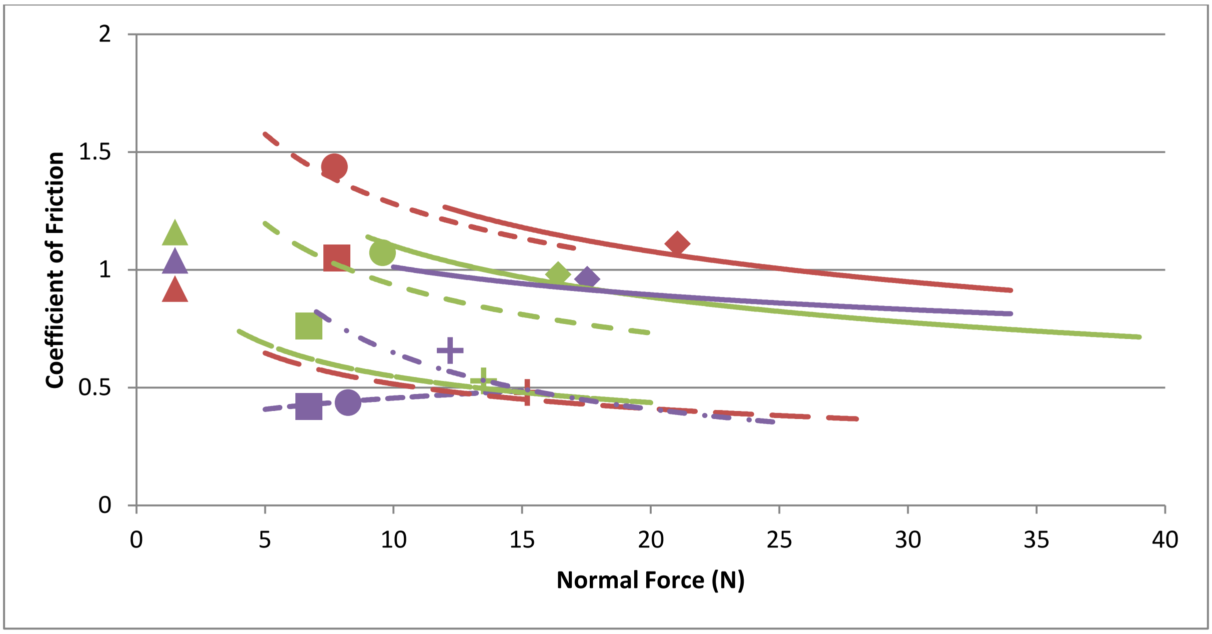


Figure 158. Comparison of dry friction results for all methods

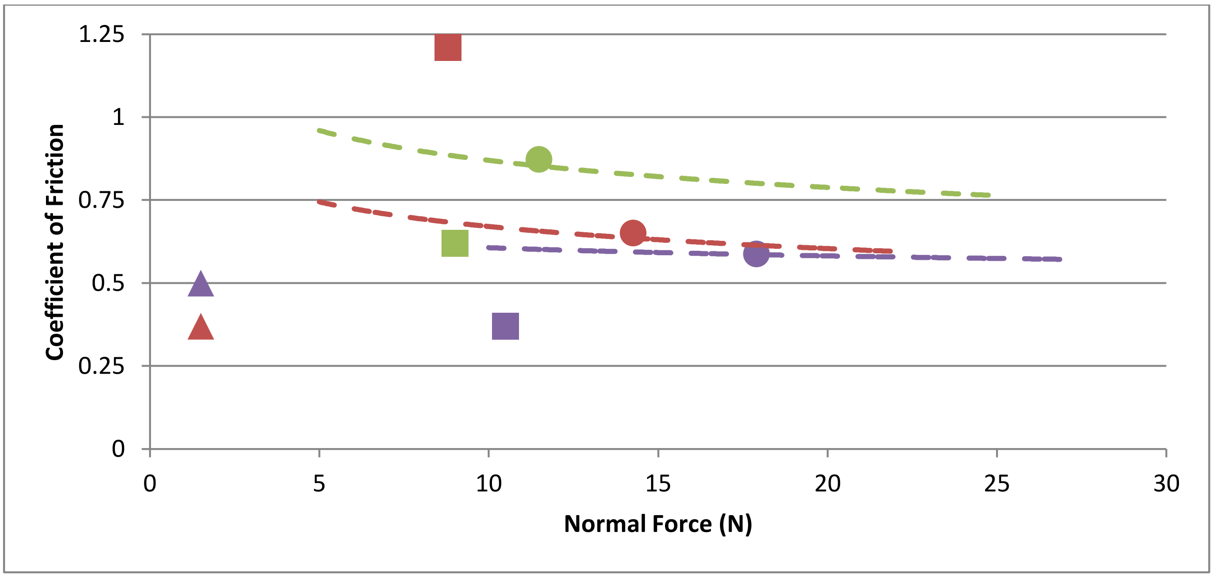


Figure 159. Comparison of wet friction results for all methods

Practitioners' perception that nitrile gloves are more slippery than latex gloves has certainly not been proved. There were differences found in the variability of results, with vinyl generally producing larger variation in measured coefficient of friction within each test. It may be that this inconsistency contributes to a lack of confidence in grasping with certain gloves. It should also be noted that the gloves were not all identical, and that the grip pattern on the nitrile gloves may have distorted that comparison between materials, particularly in the wet, where it will act to reduce wetting of the surface.

There is also a need for further study of the effect of lubrication, since most surgical tasks will be performed while the gloves are contaminated with bodily fluids. While some tests were performed in the wet and some even with artificial saliva and fat [182], more thorough investigation is needed to determine the characteristics of the gloves in these conditions. *Contact angle* measurement, which gives an indication of the ability of water or other fluids to wet a surface, was trialled during the current study, but more accurate measurement equipment is needed to produce useful results.

8.6. Conclusions

Three existing grip and friction tests (the Sheffield Finger Friction Rig, the Polyco Friction Angle Rig and the JAMAR Hand Dynamometer) were evaluated for their usefulness in measuring medical glove performance. Grip strength was not found to be significantly affected by medical gloves, and both the friction tests required modification in order to produce accurate and repeatable friction measurements.

A pinch grip rig was developed, based on previous work, with the intention of measuring both static friction and the effect of tactility on grasping force. Two subjects were tested, and the results were not conclusive, producing large variations between subjects. Further development of the test and larger-scale testing was recommended.

To remove the human element in static friction measurement, an anthropomorphic hand device was created, onto which known forces could be applied to real tools. It was validated with the pinch grip rig. Some significant differences in glove friction were found, but the variance of the results was high and they did not agree with the human pinch grip testing.

The results of the friction measurements from the various tests were compared, along with previous studies using the Sheffield rig. There was little consistency in the results between the tests, and none of the methods gives a definitive answer to the question of which glove has the highest friction in any given situation. Further study was recommended, particularly to understand the effects of lubrication and to explain the differences between practitioners' perceptions and measured results.

9. Glove Fit Evaluation

9.1. Introduction

From the inception of glove research, the effect of fit on performance has been studied (e.g. [59]). The issue is even more critical in medical gloves, since the thin nature of the gloves means a well-fitting glove can be like a ‘second skin’, almost unnoticeable, while a loose glove can distort tactile signals and inhibit dexterity, and a tight glove can restrict movement and blood-flow and hence increase fatigue. Neither the causes nor the effects of poor fit in medical gloves have been well defined (see Section 2.10 for a review of previous research on glove fit). At least two studies [61, 98] have found a relationship between fit and dexterity for chemical defence gloves, but research into medical glove fit has been limited.

Interviews with medical practitioners (Chapter 4) also highlighted the fact that provision of examination gloves in the clinical environment is less than optimal, with often only three different sizes or less available to cover the whole range of hand sizes. Practitioners are therefore often in a situation of having to perform dextrous or tactile tasks will ill-fitting gloves. A perceived relationship between fit and conformability was identified and the poor conformability of nitrile gloves compared to latex was linked by a number of participants to a corresponding reduction in tactility and dexterity. However, these perceived relationships have not been objectively tested.

In this chapter, methods of quantifying fit are explored and the relationship of glove fit in various dimensions to performance in a number of representative tasks is examined.

9.2. Selection of Fit Measurement Method

There are many different ways to quantify fit, ranging from a single dimension to many. Anthropometric data has been gathered in numerous studies over the years, particularly in the military, so that there are standard dimensions with established norms. Data from a number of studies has been collected in [184]. Robinette, Ervin et al. [61] measured 13 hand dimensions and examined the relationship between hand size and performance in dexterity tests with rubber chemical gloves, separating the results by glove size and gender. Since dexterity testing is often limited to a small sample population, reducing it further by separating into glove sizes further reduces the probability of finding significant relationships. The lack of information on glove sizes also makes detailed analysis of the causes of performance differences difficult.

Tremblay-Lutter and Weihrer [98] performed a similar experiment, measuring 18 hand dimensions, but also measuring corresponding outer dimensions on rubber chemical gloves. They then calculated ‘ease’ values for each subject in each dimension by correcting for the glove thickness to estimate the inner glove dimensions, and then subtracting the corresponding hand dimension. They also measured glove volume by obtaining the former used in moulding the glove and measuring the volume of water it displaced (why this was not used to measure the other dimensions is unclear). Chen, Cochran et al. [113] used a similar measurement method for dexterity and grip strength testing with leather and cotton gloves but only considered the glove and hand volumes when calculating ‘snugness’.

One consideration that does not seem to have been addressed in these studies is the time and resources needed to take these measurements. Many of the tests performed in this study, particularly with medical professionals, were severely limited in time. Tasron [160] took measurements with a tape measure of 14 of the dimensions described by Tremblay-Lutter prior to testing 25 candidates in a range of tasks. It was found that the anthropometry added 10-15 minutes for each candidate, and the whole testing session required a significant number of researchers. Because of time and personnel restrictions, a faster method was needed for the current study. Other methods of hand measurement (3D laser scanning, alginate moulding) were considered, but were disregarded for the same reasons.

A reduced number of measurements would minimise the time taken. Sawyer and Bennett [67] used callipers to measure six key dimensions in medical glove testing, but did not include hand width, which was identified as an issue in comfort by some of their participants. A 2009 study [99] analysed the relationships between hand dimensions in US Army data, using correlation and multiple regression analysis on three key dimension candidates (hand length, hand circumference and hand breadth) against 67 other hand and digit dimensions to determine which combination of dimensions would best represent the hand as a whole for glove sizing. They found that hand length and hand circumference correlated best with the data and thus were the most appropriate measures for glove size.

9.3. Hand Measurement Procedure

Because of the limitations on time, it was decided that the simplest way to measure hand dimensions would be to take digital photographs of each subject's dominant hand against a piece of standard graph paper. This would allow the hand dimensions to be measured with image measurement software (Meazure, C Thing Software), which was calibrated using the graph paper scale. The limitation of this method is that only two-dimensional measurements can be taken i.e. circumference cannot be measured. Only width and length were therefore used. Because a number of practitioners had noted difficulties in obtaining gloves that fitted both finger length and hand breadth, it was decided to include finger measurements as well as the whole-hand measurements recommended by Kwon et al. The selected dimensions, as defined in [184], and shown in Figure 160 were therefore:

(1) Index finger breadth: "Measured across the broadest part of the joint towards the tip of the index finger, from the side nearest the thumb to the side nearest the middle finger. Finger held straight."

(2) Index finger length: "Measured from the tip of the index finger to the base of the finger at the level of the skin web between it and the middle finger. Finger held straight."

(3) Hand breadth: "Measured across the palm of the hand at the junction between the palm and fingers, not including the thumb. The hand and fingers should be held flat [...]"

(4) Hand length: "Measured from the wrist crease directly below the pad of muscle at the base of the thumb to the tip of the middle finger. The hand and fingers should be held straight and flat [...]"

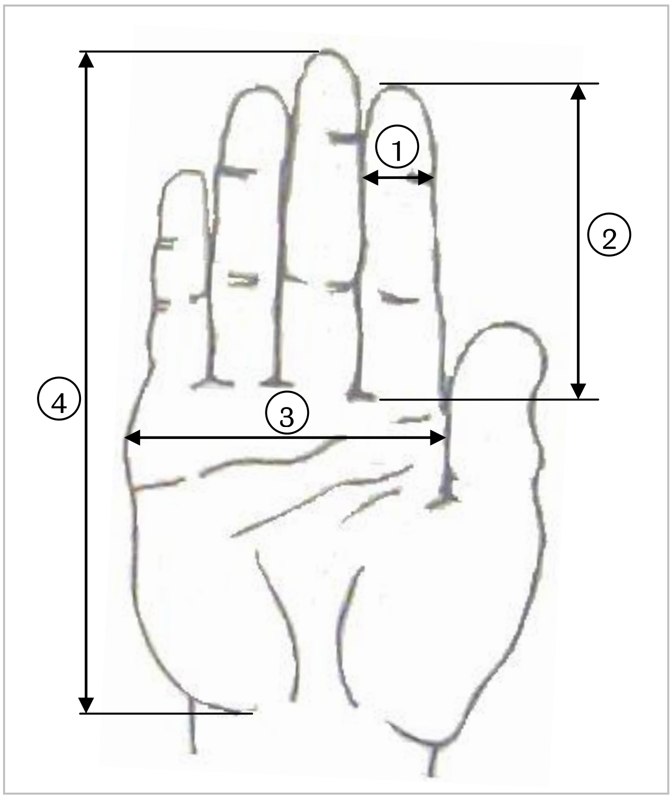


Figure 160. Hand measurement dimensions

The hand was placed flat on an A4 sheet of graph paper, which had divisions of 2mm. The photograph was taken with the line of sight perpendicular to the plane of the paper, so that dimensions were not skewed.

9.4. Glove and Ease Measurement Procedure

In order to measure the 'ease' of hands in the glove, equivalent measurements of each glove size are needed. It was decided to measure the gloves using a similar technique in order to get the closest comparison with hand dimensions. The gloves were filled with water and held flat on a surface, with the water level set so as to fully inflate the gloves, but stretch them as little as possible (see Figure 161). Because of the water involved, a plastic ruler was used instead of graph paper to calibrate the measurements. Three gloves of each size were measured and an average taken for each dimension.

Figure 161. Glove measurement technique

The 'ease' in each of the four dimensions was then calculated for each subject and glove type by subtracting the hand dimension from the glove dimension. A positive ease would thus show that the hand was smaller than the unstretched glove, while a negative one would show that the glove was stretched in that dimension in order for the hand to fit.

9.5. Representative Tests

Hand measurement was carried out for 9 tests covering friction, grip strength, dexterity, and tactility, and including specialist medical tasks carried out by qualified practitioners as well as simple tasks carried out by those inexperienced in wearing medical gloves. The tests covered were:

- SMETT 'Princess and the Pea'
- SMETT 'Bumps'
- Dental Probe Test

- Pulse Location Test
- Suturing Test
- Crawford Small Parts Dexterity Test
- Bennett Hand-Tool Dexterity Test
- JAMAR Hand Dynamometer
- Sheffield Finger Friction Test

The last four were part of Tasron's battery of tests using three sizes of nitrile glove for each subject, the measurement method of which has been described in Section 9.2. Since finger circumference rather than width was used, an adjustment was made to the measurements based on Peebles and Beverley's [184] data.

9.6. Glove Size Selection

The glove size selection of the medical practitioners who performed the Pulse Location Test was analysed using Pearson correlations. All four hand dimensions correlated significantly with each other, with the strongest correlation between finger breadth and hand breadth (0.788 p = 0.000). All 17 subjects used the same nominal size of glove for latex and nitrile. It was found that the highest correlation between hand and glove dimension was Hand Length for the latex (0.550, p = 0.022) and Finger Length (0.522, p = 0.032) for the nitrile, with no correlation for Hand Breadth and a weaker correlation for Finger Breadth.

This fits well with the information gathered in the interviews that suggested that finger length was of particular concern to practitioners in performance. The mean finger length and hand length for each glove size are shown in Figure 162 and Figure 163 respectively, with 95% confidence intervals (N.B. only one subject used

Extra-Large (XL) gloves despite having smaller hands than many of those who used Large (L)).

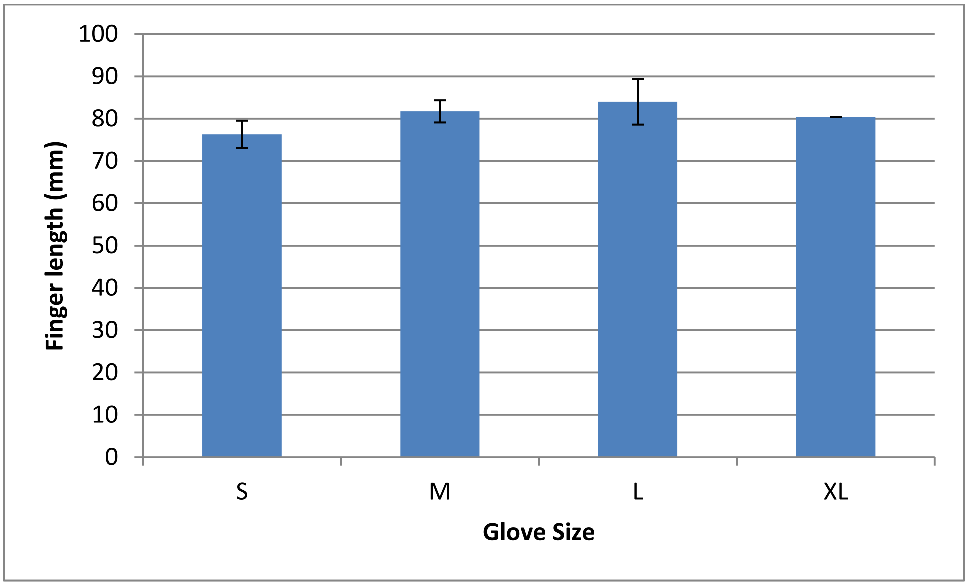


Figure 162. Mean finger length by examination glove size for 17 doctors

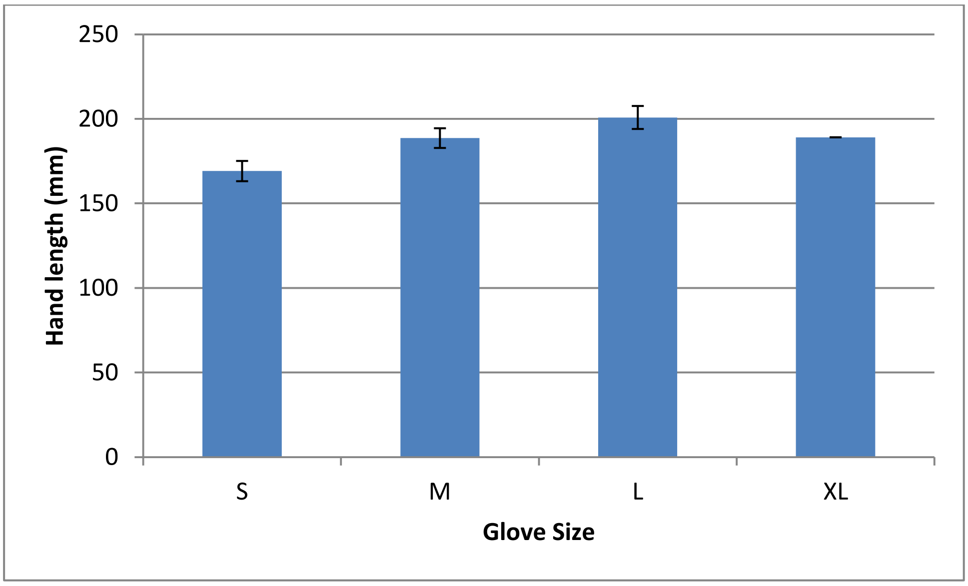


Figure 163. Mean hand length by examination glove size for 17 doctors

When the ‘ease’ for three of the testing populations was compared, it was found that doctors generally chose looser gloves than engineering students or dental students. The average finger length ease is shown in Figure 164. Negative values indicate that the finger dimension is larger than the glove and the glove is therefore stretched – larger negative numbers indicate greater tightness. Obviously the doctors had the most experience of using gloves, and since they tend to wear them for long periods, they may be more aware of discomfort and fatigue from tight gloves. It can also be seen that the nitrile glove ease was less than that of latex, which was mainly due to the fact that the nitrile gloves were on average 2mm shorter in finger length.

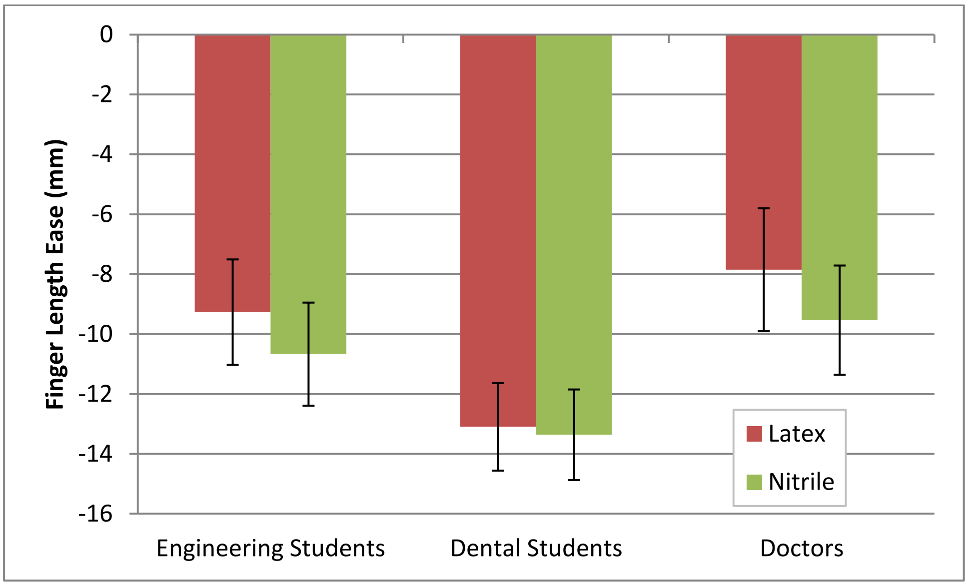


Figure 164. Mean finger length ease for three testing populations

9.7. Method of Analysis

The mean difference to the 'No Gloves' score for each glove condition as a percentage of the mean 'No Gloves' score was used for the analysis in order to reduce the effect of between-subject variation in ability. It was expected that any relationship between ease and performance would be in the form of a peak at the optimal ease from which performance would drop off on either side. Therefore, linear regression would not be an appropriate form of analysis. Instead, for each test population, in each of the four dimensions, the subjects were separated into equally-spaced ranges of 'ease'. For each test, the mean performance of the subjects in each range could then be calculated and the significance of any differences between groups analysed to determine whether ease in any dimension had a significant effect on performance in each test. For Tasron’s tests, which used three sizes of nitrile glove for each subject, the results for all three sizes were included in the same analysis.

9.8. Results

The results did not deviate significantly from normality on the whole, so independent-samples t-tests were used to analyse the significance of differences in performance between ranges of ease.

9.8.1. Tactility tests

The effect of fit or ‘ease’ on performance in four tactility-based tests (SMETT ‘Princess and the Pea’, SMETT ‘Bumps’, Dental Probe Test and Pulse Location Test) was examined. Ease in the four dimensions was plotted against performance for each test, and those plots where any trend was seen are shown in Figures 166 - 174. A key to each of the graphs is shown in Figure 165.

Figure 165. Key for Performance-Ease graphs (Figures 166 - 183)

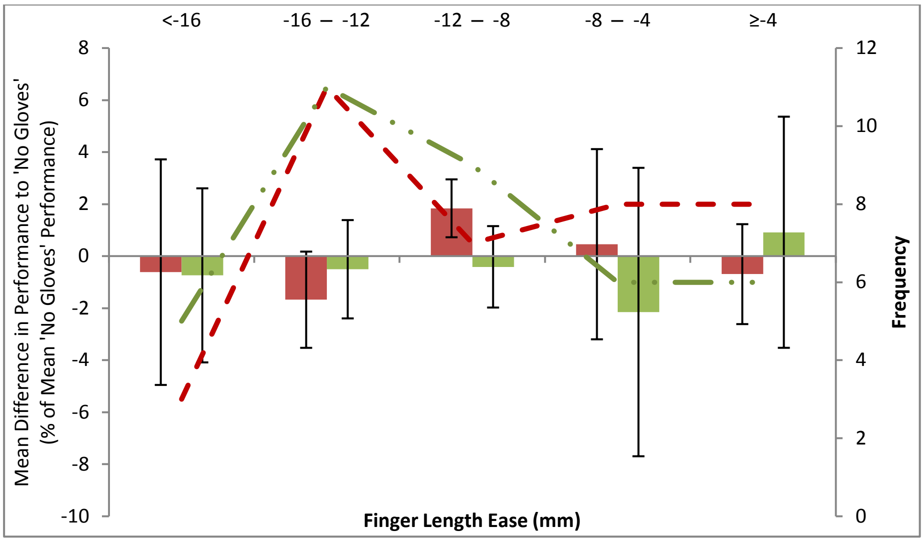


Figure 166. Mean relative performance in the SMETT 'Princess and the Pea' test for five categories of Finger Length Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

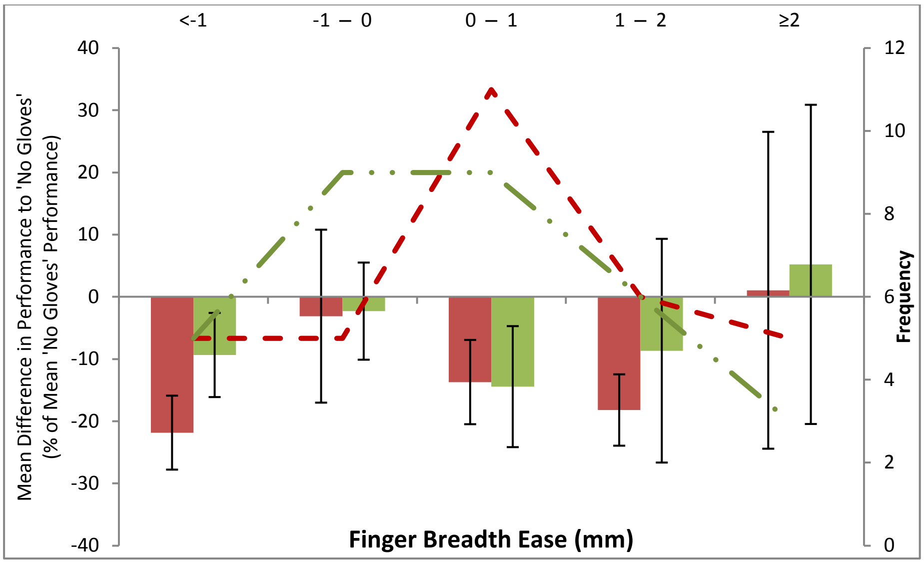


Figure 167. Mean relative performance in the SMETT 'Bumps' test for five categories of Finger Breadth Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

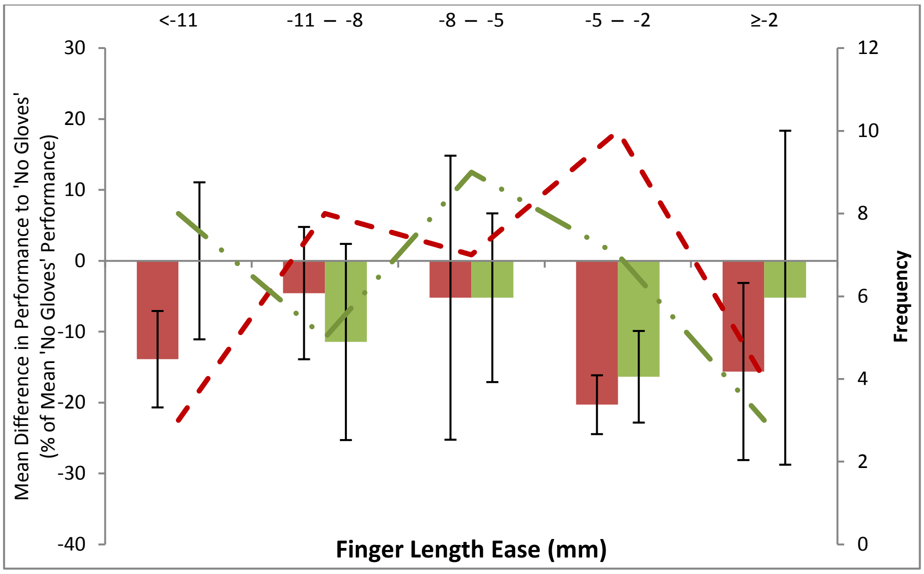


Figure 168. Mean relative performance in the SMETT 'Bumps' test for five categories of Finger Length Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

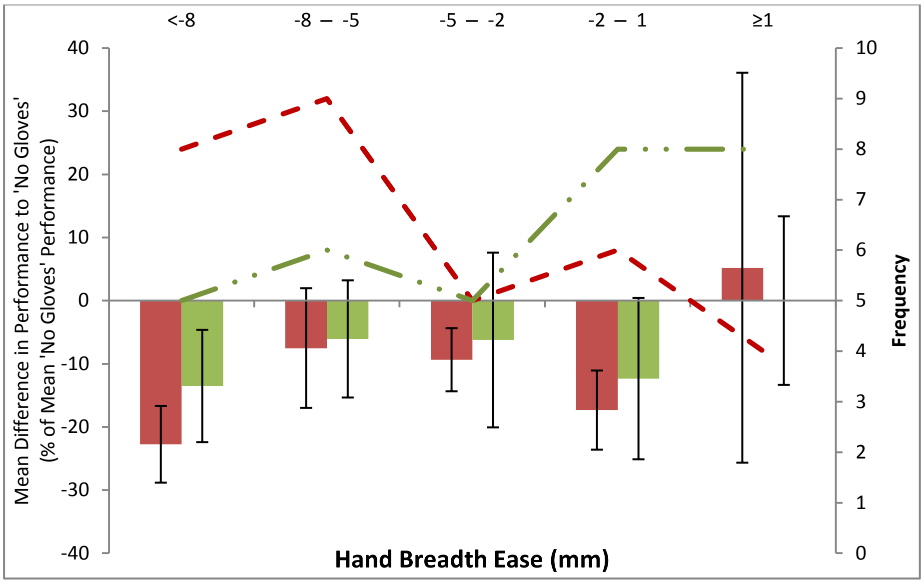


Figure 169. Mean relative performance in the SMETT 'Bumps' test for five categories of Hand Breadth Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

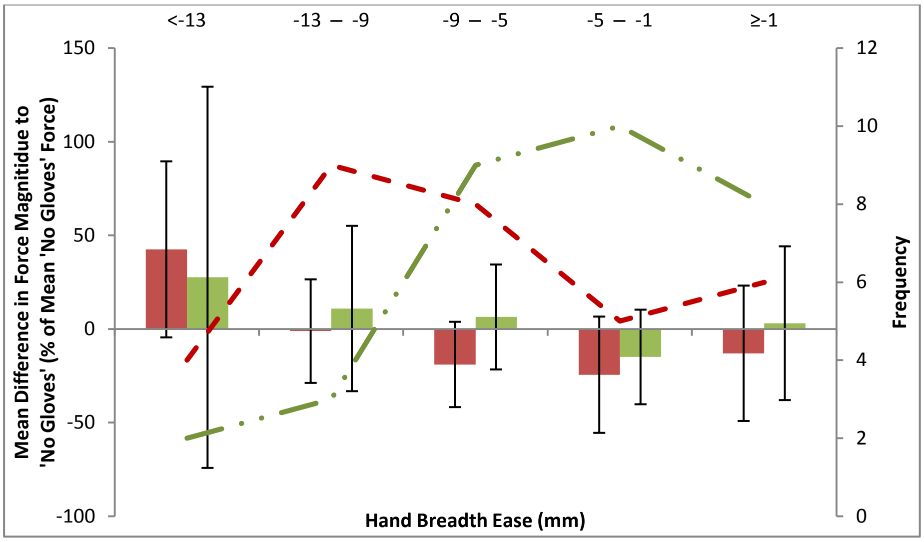


Figure 170. Mean relative performance in the Dental Probe Test for five categories of Hand Breadth Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

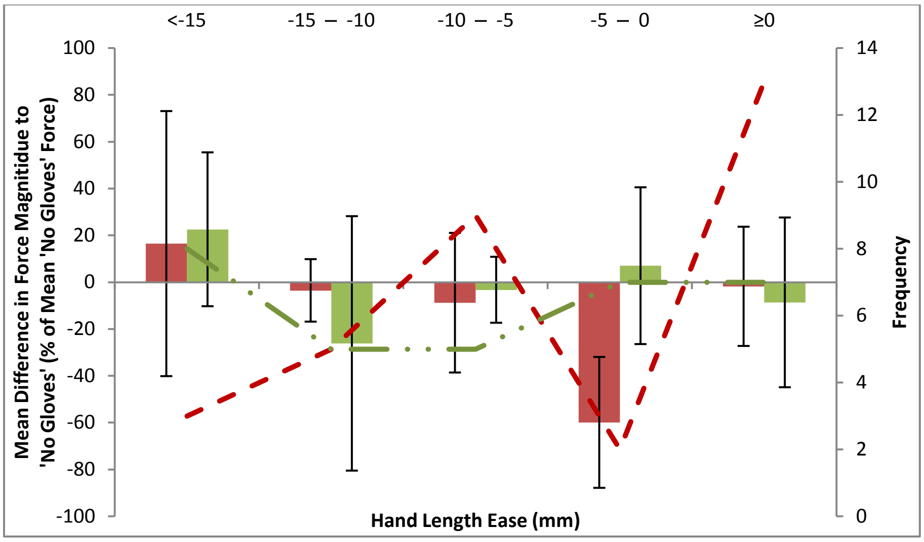


Figure 171. Mean relative performance in the Dental Probe Test for five categories of Hand Length Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

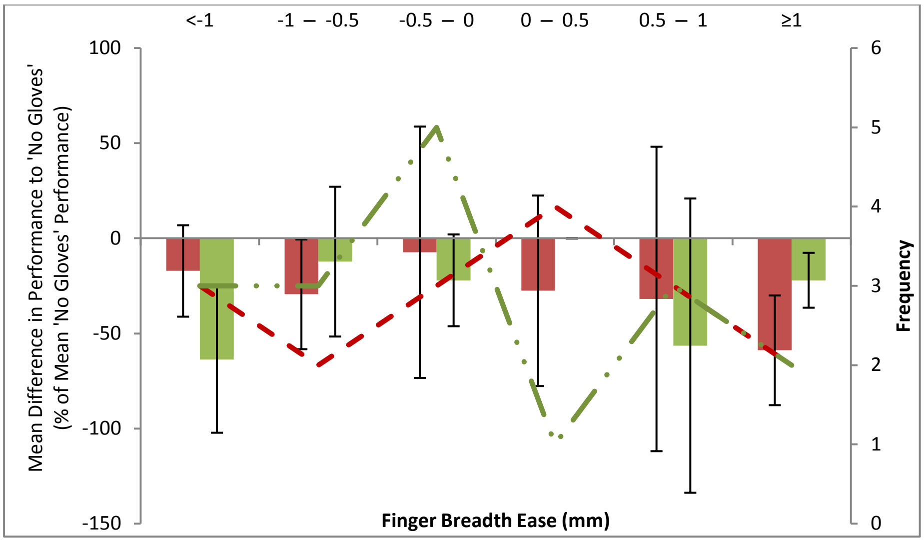


Figure 172. Mean relative performance in the Pulse Location Test for six categories of Finger Breadth Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

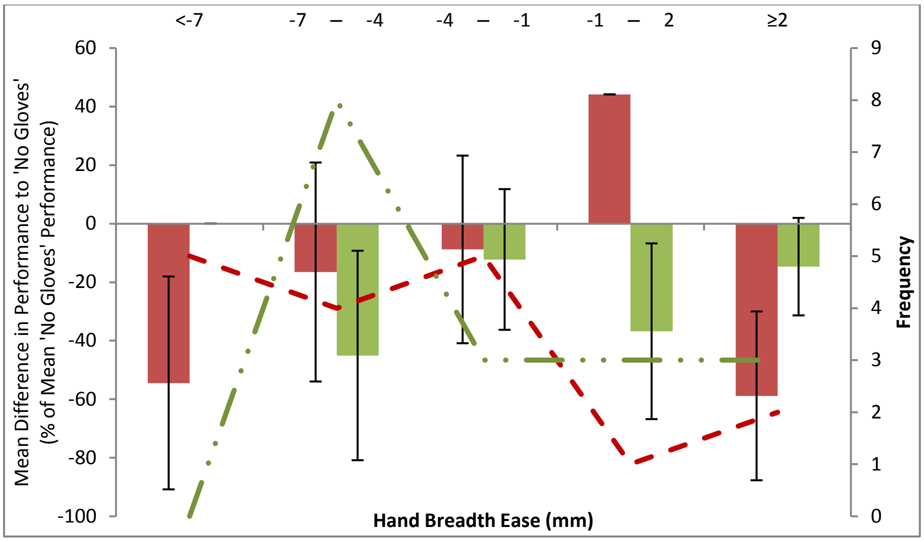


Figure 173. Mean relative performance in the Pulse Location Test for five categories of Hand Breadth Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

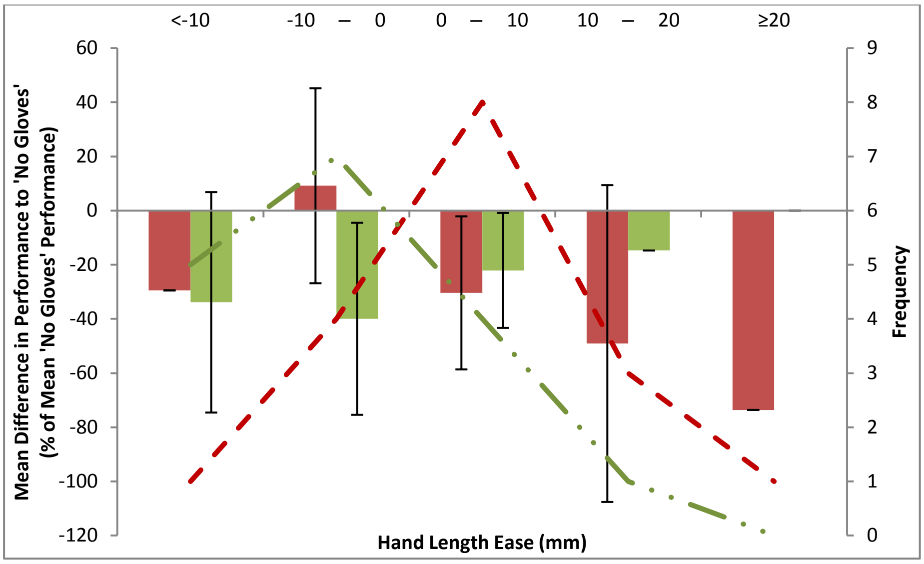


Figure 174. Mean relative performance in the Pulse Location Test for five categories of Hand Length Ease with two examination glove types (with 95% confidence intervals and number of candidates of subjects in each category)

Table 46 is a summary of the relationships found. Because of the small sample size, *p* values of less than 0.2 are included in the table as these may approach significance with a larger sample.

Table 46. Effect of glove fit on performance in tactility tests including increase and decrease in ease for a significant reduction in performance from the optimum (*p* values shown in brackets)

Ease dimension	(All values in mm)	P&P		Bumps		Dental		Pulse	
		Latex	Nitrile	Latex	Nitrile	Latex	Nitrile	Latex	Nitrile
Finger Breadth	Mean			0.4	0.3			0.3	0.1
	Optimum			~ -0.5	~ -0.5			~ -0.25	~ -0.6
	Decr. for Sig. Diff.*			>2 (0.056)	NS			NS	>0.75 (0.104)
	Incr. for Sig. Diff.*			>0.5 (0.103)	>1 (0.075)			NS	NS
Finger Length	Mean	-9.3	-10.7	-6.2	-7.6				
	Optimum	~ -10	~ -12	~ -8	~ -7				
	Decr. for Sig. Diff.*	**~ 4 (0.014)**	NS	NS	NS				
	Incr. for Sig. Diff.*	>6 (0.051)	NS	**~6 (0.005)**	>3 (0.160)				
Hand Breadth	Mean			-5.3	-2.4	-7.7	-4.5	-2	-2
	Optimum			~-6	~-5	~ -4	~ -3	~ 0	~ -0.5
	Decr. for Sig. Diff.*			**>1.5 (0.021)**	NS	**>6 (0.025)**	NS	>-4.5 (0.102)	NS
	Incr. for Sig. Diff.*			>6 (0.156)	NS	NS	NS	>1 (0.139)	NS
Hand Length	Mean					-4.8	-2.0	4.3	-4.2
	Optimum					~ -2.5	~ -12	~ -5	~ -2/>2
	Decr. for Sig. Diff.*					**10 (0.009)**	NS	>0.5 (0.134)	NS
	Incr. for Sig. Diff.*					>2.5 (0.062)	NS	NS	NS

*Significant differences ($\alpha = 0.05$) shown in bold, NS = not significant, $p \geq 0.2$

9.8.2.Dexterity tests

The effect of fit or 'ease' on performance in four dexterity-based tests (Suturing, Crawford SPDT 'Pins and Collars', Crawford SPDT 'Screws' and Bennett Hand-Tool Dexterity Test) was examined. Ease in the four dimensions was plotted against performance for each test, and those plots where any trend was seen are shown in Figures 175 - 181. Table 47 is a summary of the relationships found.

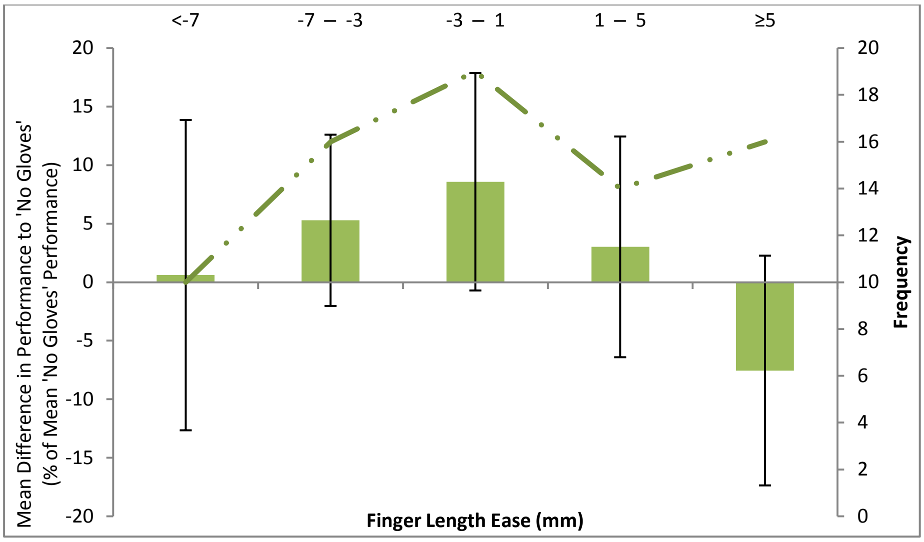


Figure 175. Mean relative performance in the Crawford 'Pins and Collars' test for five categories of Finger Length Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

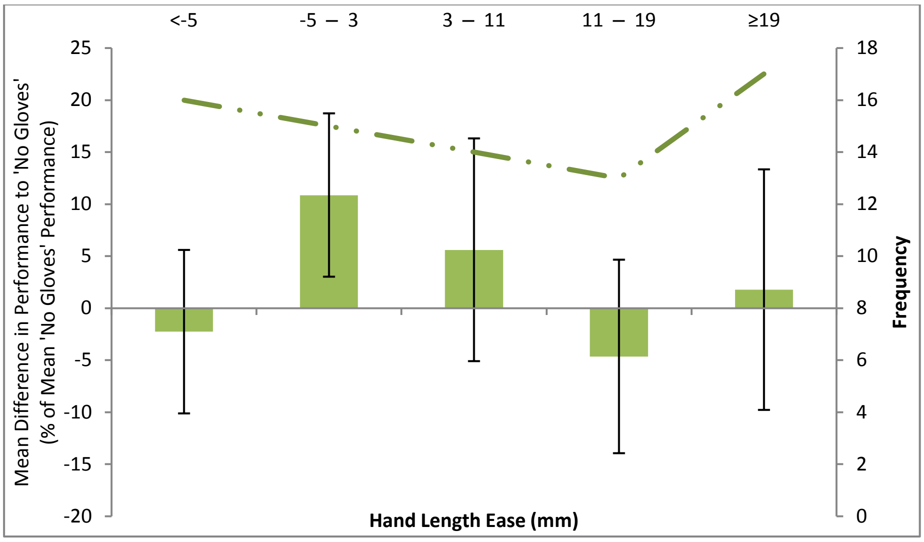


Figure 176. Mean relative performance in the Crawford 'Pins and Collars' test for five categories of Hand Length Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

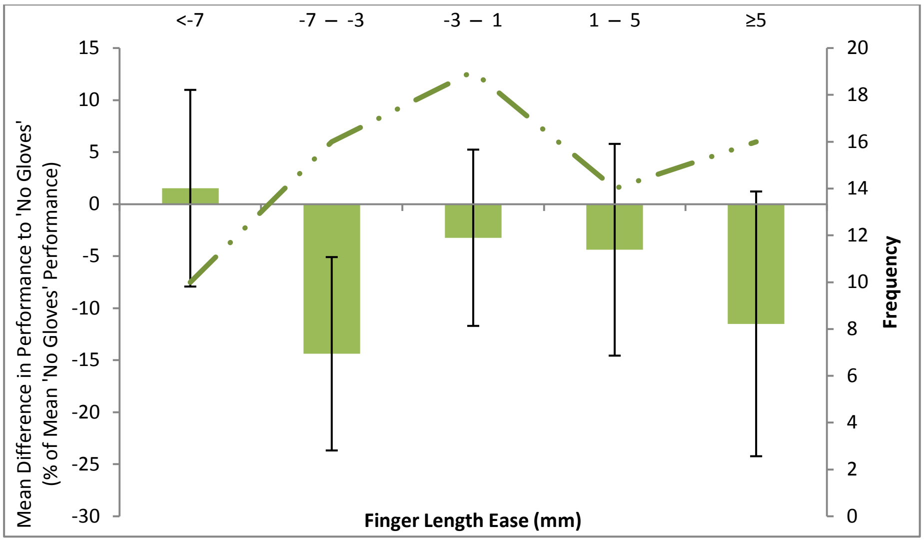


Figure 177. Mean relative performance in the Crawford 'Screws' test for five categories of Finger Length Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

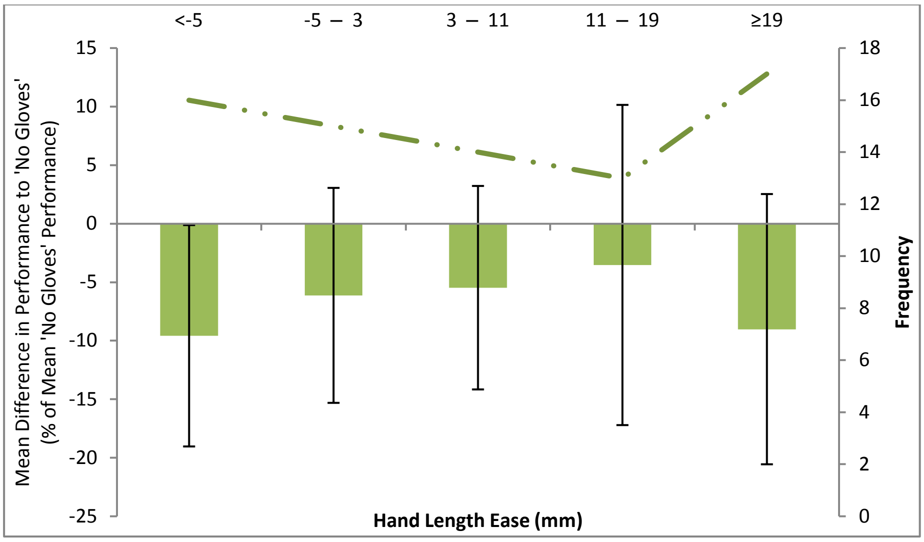


Figure 178. Mean relative performance in the Crawford 'Screws' test for five categories of Hand Length Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

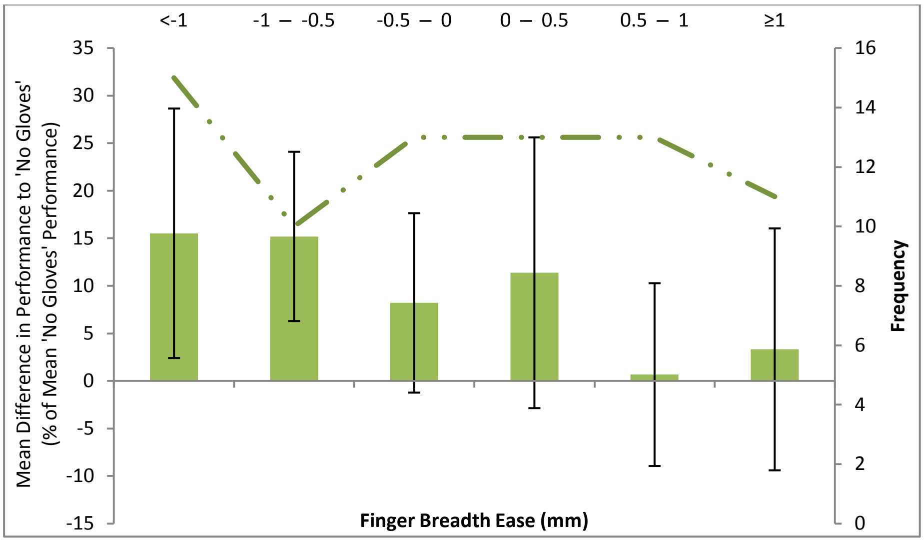


Figure 179. Mean relative performance in the Bennett H-TDT test for six categories of Finger Breadth Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

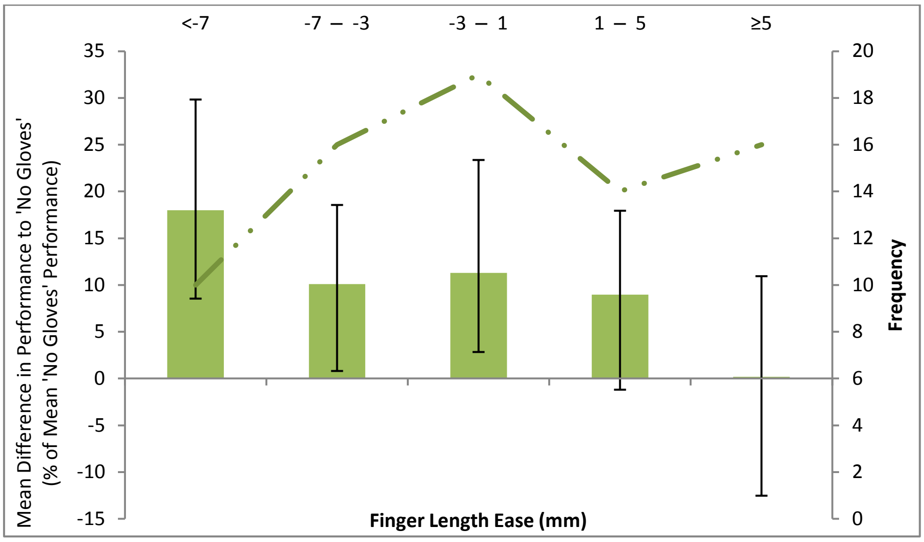


Figure 180. Mean relative performance in the Bennett H-TDT test for five categories of Finger Length Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

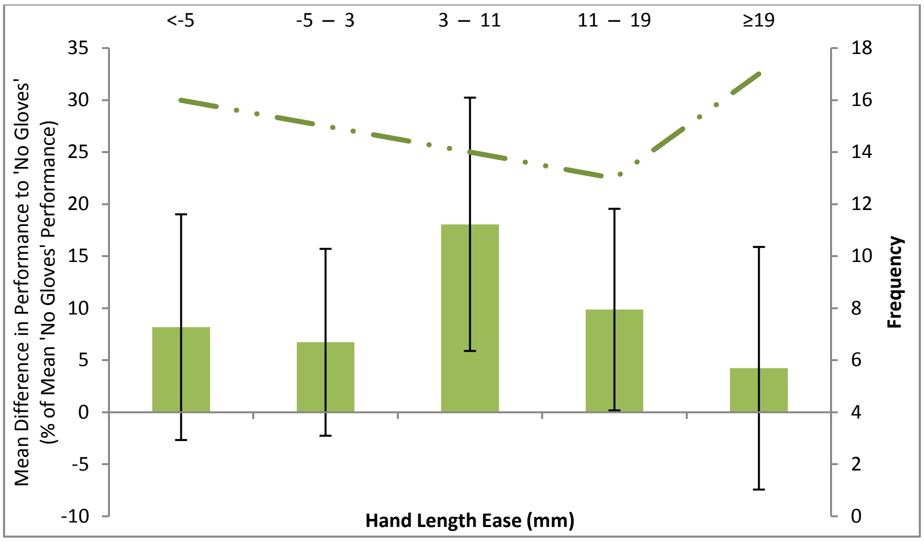


Figure 181. Mean relative performance in the Bennett H-TDT test for five categories of Hand Length Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

Table 47. Effect of glove fit on performance in dexterity tests including increase and decrease in ease for a significant reduction in performance from the optimum (*p* values shown in brackets)

Ease dimension	(All values in mm)	Suturing		'Pins & Collars'	'Screws'	Bennett HT-DT
		Latex	Nitrile	Nitrile (Best-Fit)	Nitrile (Best-Fit)	Nitrile (Best-Fit)
Finger Breadth	Mean					-1.1
	Optimum					<-1
	Decr. for Sig. Diff.*					?
	Incr. for Sig. Diff.*					**1.5 (0.047)**
Finger Length	Mean			0.1	0.1	0.1
	Optimum			~ -1	~ 0	<-7
	Decr. for Sig. Diff.*			NS	>4 (0.091)	?
	Incr. for Sig. Diff.*			**>6 (0.028)**	NS	**>2 (0.045)**
Hand Breadth	Mean					
	Optimum					
	Decr. for Sig. Diff.*					
	Incr. for Sig. Diff.*					
Hand Length	Mean			7.1	7.1	7.1
	Optimum			~ -1	~ 15	7
	Decr. for Sig. Diff.*			**>4 (0.028)**	NS	>8 (0.150)
	Incr. for Sig. Diff.*			**16 (0.018)**	NS	>16 (0.120)

*Significant differences ($\alpha = 0.05$) shown in bold (*p* values in brackets), NS = not significant, $p \geq 0.2$

9.8.3. Other tests

The effect of 'ease' on grip strength and dynamic finger friction was analysed. There were found to be trends in the relationships between Hand Length Ease and hand dynamometer performance (Figure 182) and between Finger Breadth Ease and coefficient of dynamic friction (183). Table 48 is a summary of the relationships found.

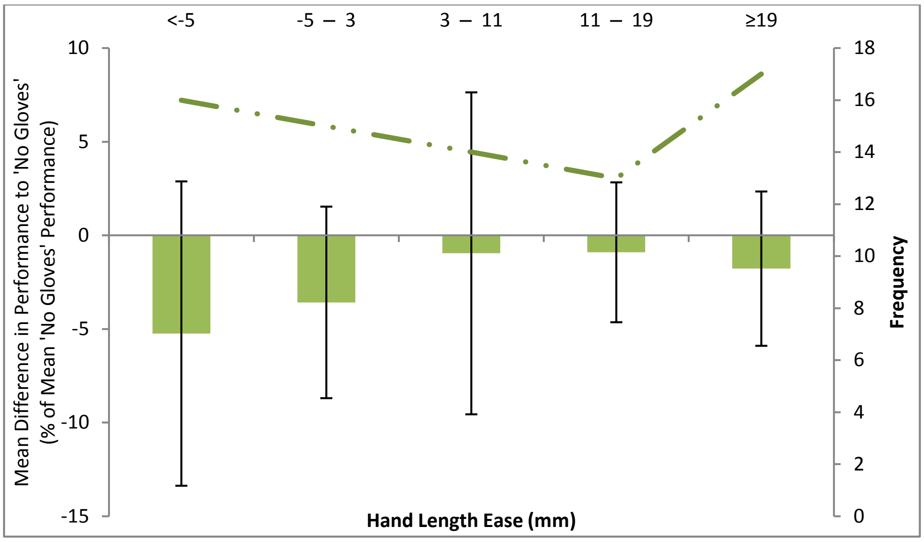


Figure 182. Mean relative performance in the JAMAR Hand Dynamometer test for five categories of Hand Length Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

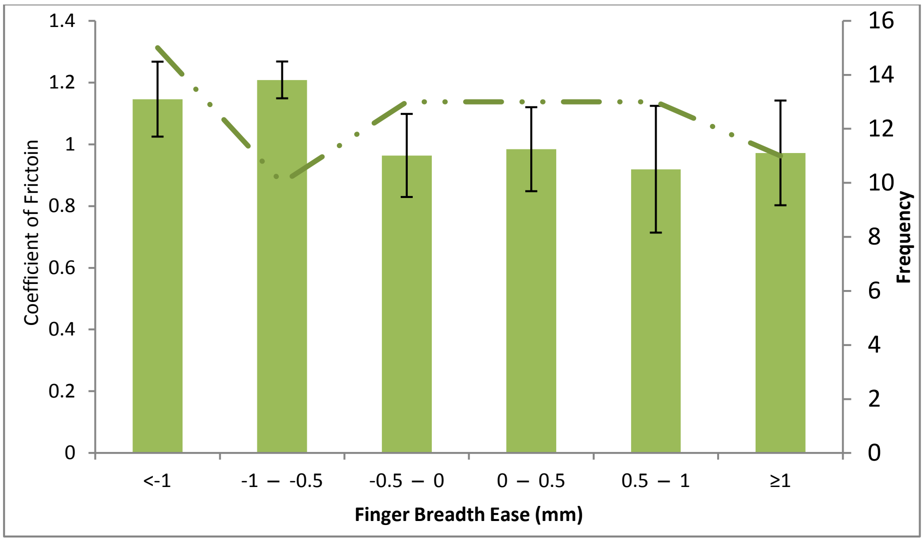


Figure 183. Mean coefficient of dynamic friction in the Sheffield Finger Friction test for five categories of Finger Breadth Ease with nitrile examination gloves (with 95% confidence intervals and number of candidates of subjects in each category)

Table 48. Effect of glove fit on grip strength and dynamic friction including increase and decrease in ease for a significant reduction in grip strength performance from the optimum or a significant change in coefficient of friction (*p* values shown in brackets)

Ease dimension	(All values in mm)	JAMAR	Finger Friction
		Nitrile (Best-Fit)	Nitrile (Best-Fit)
Finger Breadth	Mean		-1.1
	Optimum		n/a
	Decr. for Sig. Diff.*		NS
	Incr. for Sig. Diff.*		**0.5 (0.005)**
Hand Length	Mean	7.1	
	Optimum	~ 11	
	Decr. for Sig. Diff.*	NS	
	Incr. for Sig. Diff.*	NS	

*Significant differences ($\alpha = 0.05$) shown in bold (*p* values in brackets), NS = not significant, $p \geq 0.2$

9.9. Discussion

A relationship between hand breadth ease and performance was seen in three of the four tactility tests. The most significant reduction in performance occurred with a decrease in hand breadth ease in the latex gloves. Trends were less distinct for nitrile, and the effect of ease on performance was not significant in any dimension. Hand length ease for latex gloves had a significant effect on the Dental Probe Test mean peak force, while finger length ease for latex gloves had a significant effect for the ‘Princess and the Pea’ test.

The importance of hand breadth ease in tactility is a surprising result. Because of the small sample size and the variation between subjects, it is difficult to be confident in the result. When the effect of four factors on ten dependent variables is examined, some trends will emerge at random. A larger sample size is necessary to confirm the results. However, what is clearer from the results is that wearing gloves that are too tight has a more significant effect on tactility than wearing gloves that are too loose. One possible explanation for the result is that gloves that are too tight will reduce blood-flow to the fingertips, which might reduce tactile sensitivity. This was certainly the experience in the preliminary testing with the Semmes-Weinstein monofilaments, where tight gloves often caused 'pins and needles', which masked the tactile signals.

It is also surprising that fit had a greater effect with the latex gloves than with nitrile in the tactility tests, since the interviews with practitioners suggested that more people had an issue with the fit of nitrile gloves. This may be partly due to the fact that the mean ease with the nitrile gloves was larger in the hand breadth dimension, where the most significant differences occurred, than the latex, so that problems with tight gloves were less common. Practitioners commented during the interviews that, because of the lower elasticity of the nitrile gloves, they would tend to wear looser-fitting ones, as they would not be able to get tighter ones on, whereas with the latex, the tighter gloves could be stretched over the hand – this might then cause restriction and loss of performance. However, more data is needed to confirm or reject this apparent difference between the gloves, which may simply be an artefact of the small sample size.

It should also be noted that the effect of glove fit was more pronounced in the dexterity tests, most of which used only nitrile gloves, making it difficult to fully compare the two glove types in terms of the effect of fit on performance. It was generally found that wearing looser-than-optimal gloves produced a more significant reduction in dexterity than wearing tighter gloves. Hand length and finger length ease had the most consistent effect across the tests. These results agree with what was found in the Purdue Pegboard testing (Chapter 6), that loose latex gloves perform significantly worse in dexterity testing than ‘best-fit’ gloves. The increases in finger length and hand length from the Medium to the Extra-Large latex gloves are 7mm and 29mm respectively, which correspond well with the increases that produced significant differences in dexterity in the fit analysis. Participants in the tests commented that loose material on the fingertips got trapped in tools, parts and holes and generally made picking objects up more clumsy, as fingertip sensation was reduced. Finger length ease and hand length ease will obviously be related, since finger length is included in the hand length measurement. However, it is interesting that a bigger effect is seen in reducing hand length ease from the optimum than reducing finger length ease. This may be due to the restriction in flexion of the hand and particularly the thumb that occurs with tightness across the palm, reducing the ability to manipulate objects.

The JAMAR Hand Dynamometer results did not show significant differences, although there was an apparent trend with hand length ease. It is not expected that glove size would significantly affect grip strength because of the thinness of the gloves, although it could be that tight gloves provide some restriction and therefore reduction in force.

In the Sheffield Finger Friction results, the two tightest categories of finger breadth ease produced much higher friction than the loosest four. This result can be explained from the nature of rubber friction. With two smooth surfaces, in this case a tight glove on smooth steel, the mechanism will be mostly adhesive, and therefore dependent on contact area. With a loose glove, wrinkles will form as the finger slides, reducing the contact area of the glove with the surface and thus reducing adhesive friction. The looser gloves also have higher variance in general, which is likely to be a result of the inconsistent nature of the contact with a wrinkled surface.

In terms of optimum ease, all the tactility tests had a similar optimum finger breadth ease of -0.25 to -0.6 mm for both the latex and nitrile, while the Bennett test was less clear, but achieved the highest scores with ease values less than -0.5. The actual mean ease (ignoring Tasron's results because she measured circumference not width) was between 0.1 and 0.4 mm.

The optimum finger length ease was around -9mm in both the latex and nitrile for the tactility tests and less than -7mm for the Bennett test, but was less clear for the other dexterity tests. In the tactility tests, the actual mean ease was between -6 and -9mm for latex and between -8 and -11mm for nitrile, whereas for Tasron's dexterity tests the mean was much higher at 0.1mm. This could be because her subjects were predominantly Asian females who had smaller hands on average than in some of the other tests, and perhaps chose over-sized gloves.

The optimum hand breadth ease was around -5 to -6mm for the Bumps test, -3 to -4mm for the Dental Probe Test and 0 to -0.5mm for the Pulse Location Test, while the actual mean was around -5mm for latex and -3mm for nitrile. It had no discernible effect on dexterity or grip strength.

The optimum hand length ease varied from -2 to -12mm for the tactility tests (Dental Probe Test and Pulse Location Test), with the mean ease varying between 4 and -5mm for different gloves and populations (dentists or doctors). For the dexterity tests, the optimum varied between -1 and 15mm, with the mean being 7.1mm. However, there were only significant effects in the 'Pins and Collars' and Dental Probe tests, so the optimum is more likely to be in the range -1 to -2.5mm.

While there was a large spread of ease values in each dimension, on average, subjects chose 'best-fit' gloves that were close to the overall optimum in most dimensions, apart from Tasron's subjects who generally chose larger-than-optimum gloves. There was no consistent difference in optimum ease between latex and nitrile gloves. Because of the lower flexibility of nitrile gloves, higher optimum ease values were expected, since tighter latex gloves are able to stretch more easily, but in fact both types of glove appeared to show negative optimum ease values in all dimensions. Whether these optimum ease values for best performance relate to what is most comfortable or perceived to be best by practitioners has not been examined, but could be a subject for further study.

A fit evaluation of chemical defence gloves using dexterity tests [98] determined that the optimal ease values for index finger length, finger breadth and hand breadth were -2.7mm, -1.9mm and 17.5mm respectively. The finger dimensions agree fairly well with those presented here, although Tremblay-Lutter and Weihrer's results were based primarily on subjective ratings of best fit.

Because of the need to divide the data into enough fit categories to see a trend, the sample size was too small in all tests to see much significance in the differences. While some of the trends can be explained, there is not enough consistency in the results to draw firm conclusions. However, there is enough evidence of the effect of fit on both tactility and dexterity to justify larger-scale testing. There does appear to be a range of acceptable ease values within which performance is not significantly affected. However, the fact that a proportion of the subjects were outside this band in at least one dimension suggests that the current range of examination glove sizes may not be sufficient to avoid significant reduction in performance due to the gloves for some practitioners. Both the number of sizes available and the ratios between the four ease dimensions should be considered further.

9.10. Conclusions

Analysis of the effect of glove fit on performance in a number of the tests included in this study showed that:

- There were significant effects of fit in various dimensions on performance in a number of the tests;
- Glove fit had a more significant effect on dexterity than on tactility;
- Overly-tight gloves (particularly in finger breadth) reduced tactility more than overly-loose ones;
- The reverse was true for dexterity, where loose gloves, particularly in hand and finger length, caused the largest reduction in performance;
- Tight gloves produced the highest coefficients of friction with dry steel;
- Glove fit did not significantly affect grip strength;
- In general, glove fit appeared to have a more significant effect on performance with latex gloves than with nitrile, contrary to practitioners' perceptions.

Optimum values for 'ease' (difference between hand and glove dimensions) varied between tests, with all being negative i.e. glove mould size should be less than hand size. On average, people chose gloves that were fairly close to the optimum, but a sizeable proportion was outside the band of acceptance in the key dimensions. Further study of the effects of fit on performance, and of the current method of glove sizing and mould design, was therefore recommended in order to determine whether the sizes currently provided are the most appropriate.

10. Perceived vs. Measured Performance

10.1. Introduction

Interviews with medical practitioners in the early stages of the project (Chapter 4) showed that many practitioners had strong views on the relative effects of different gloves on performance. Because of the recent replacement of latex examination gloves with nitrile alternatives in most NHS Trusts, most of these views centred on the differences between the two materials, particularly in the way they conform to the hand and the slipperiness of the nitrile, with the vast majority preferring latex. However, previous testing at the University of Sheffield [25, 181, 182] had shown some evidence to the contrary.

Many of the previous medical glove studies did not find any significant differences in performance between gloves (see Chapter 2). It was therefore important to determine how the perceived and objective performance of gloves are related and whether the lack of significant performance differences in some tests was a result of poor test resolution or whether perceived differences are purely psychological. If the former is the case, then test methods need further improvement; if perceived differences do not translate to objective performance decrease, then further investigation of the effects of gloves on confidence and stress levels and how this affects longer-term performance may be worthwhile.

10.2. Methodology

Data collection. Simultaneous subjective and objective performance testing of medical gloves has been limited. Most subjective measurements have related to ease and comfort (e.g. [59, 98]). Norton and Hignett [83] used a five-point Likert scale (agree/disagree) to measure, among other things, the ‘hindering effect on ability to carry out task’. However, the limitation of a Likert scale is that it makes it difficult to measure the relative size of differences between multiple conditions. It was decided instead to use magnitude estimation, in which subjects set their own scale and are therefore free to give as small or large a rating as they feel is appropriate to represent the difference. (See Chapter 7 for further explanation of the method.)

The subjective measurements were included in four of the new tests (SMETT ‘Bumps’ and ‘Princess and the Pea’, Pulse Location Test and Suturing Test). After the subjects had completed the test in *all* conditions, they were asked to rate their performance for each hand condition, using a scale of their choice so that a score of twice as much represented performance that was twice as good. They were not shown the objective score (although it was possible to estimate their score in some of the tests such as the Pulse Location Test).

Tasron [160] also took subjective measurements in her dexterity tests. She asked subjects to rate the level of difficulty experienced in performing the task from 1 to 10 for each hand condition. The results for the Crawford Small Parts Dexterity Test and Bennett Hand-Tool Dexterity Test are analysed here.

Data analysis. The subjective scores for each subject were normalised using the method described in Chapter 7. In order to analyse the relationship between subjective and objective scores for each test, the same process of normalisation was applied to the test scores. This accounts for the difference in performance between subjects, which was particularly significant in the ‘Princess and the Pea’ test, where different mouldings produced vastly different scores. A comparison of the normalised subjective and objective scores then gives a measure of whether the ranking and scaling of performance correlate for the two measures. The Pearson correlation between scores for all hand conditions was calculated for each test and the average normalised subjective and objective score for each hand condition compared. 95% confidence intervals (CI) were calculated for the geometric mean of the normalised perceived performance scores using:

$$\mathrm{CI}_{\text{geometric mean}}(\text{normalised scores}) = \exp\{\mathrm{CI}_{\text{arithmetic mean}}[\ln(\text{normalised scores})]\}$$

Significance of differences was tested using t-tests (which analyse differences in arithmetic mean) on the log perception scores.

10.3. Results

10.3.1. SMETT 'Bumps'

The relationship between perceived performance and bump detection rate is shown in Figure 184. The Pearson's correlation analysis showed a moderate, positive correlation between the variables ($r = 0.567$, $N = 96$, $p < 0.001$). This suggests that subjects were able to judge their level of performance in the test fairly well.

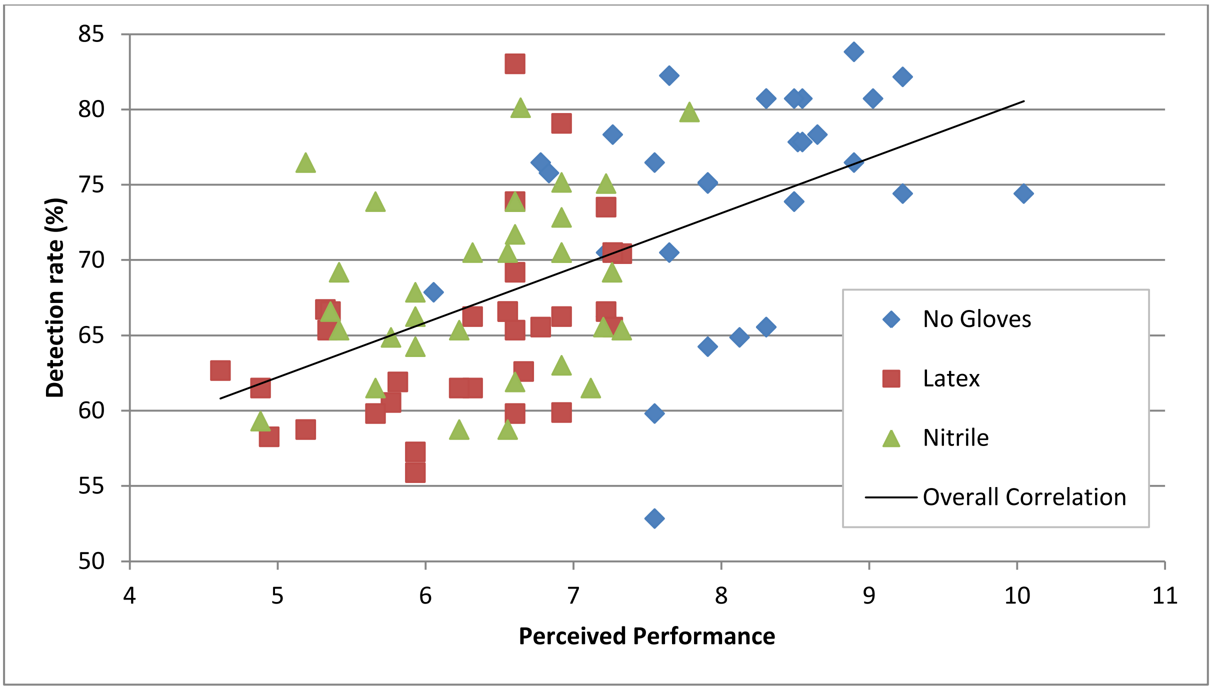


Figure 184. Relationship between detection rate and perceived performance in the SMETT 'Bumps' (normalised scores)

The average normalised objective and subjective scores for each hand condition are shown in Figure 185.

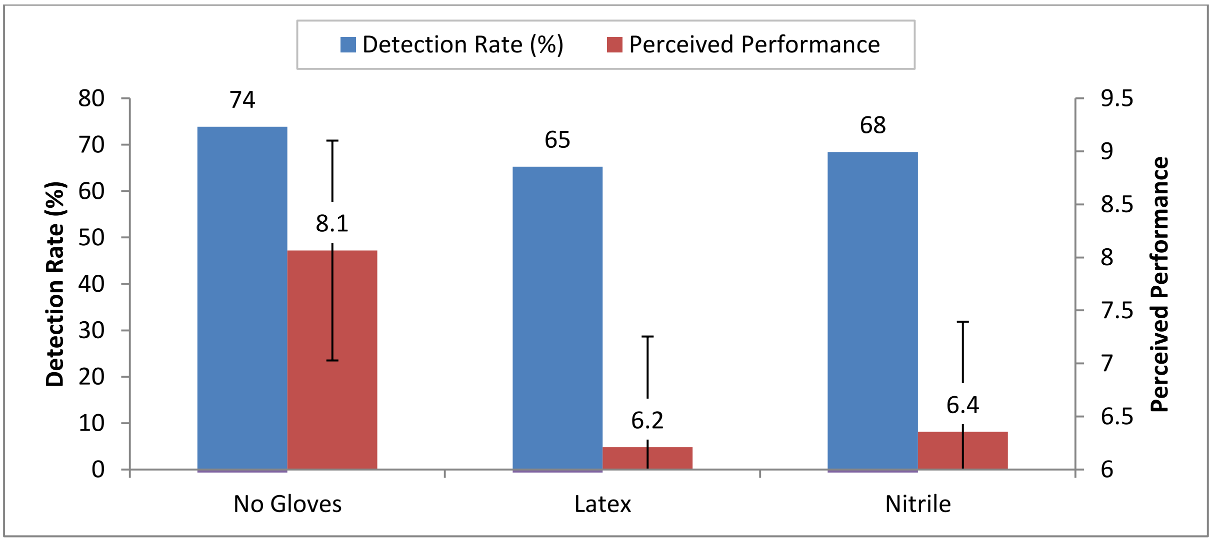


Figure 185. Average normalised objective and subjective scores for 32 subjects in three hand conditions in the SMETT 'Bumps' (with 95% confidence intervals for perceived performance)

Only one of the three datasets showed significant deviation from normality in the log perception scores, so paired t-tests were used for significance testing.

Subjects perceived performance in the ungloved condition to be significantly better than in the two gloved conditions ($p \leq 0.003$), but there was no significant perceived difference between the gloves ($p = 0.528$). This agrees with the objective results, and in fact the significance of the differences between the gloves was much greater in the objective results ($p = 0.080$) than in the subjective.

10.3.2. SMETT 'Princess and the Pea'

The relationship between perceived performance and detection rate in the SMETT 'Princess and the Pea' is shown in Figure 186. The Pearson's correlation analysis showed only a very weak, positive correlation between the variables ($r = 0.141$, $N = 117$, $p = 0.130$), with perceived performance being fairly unrelated to actual detection rate.

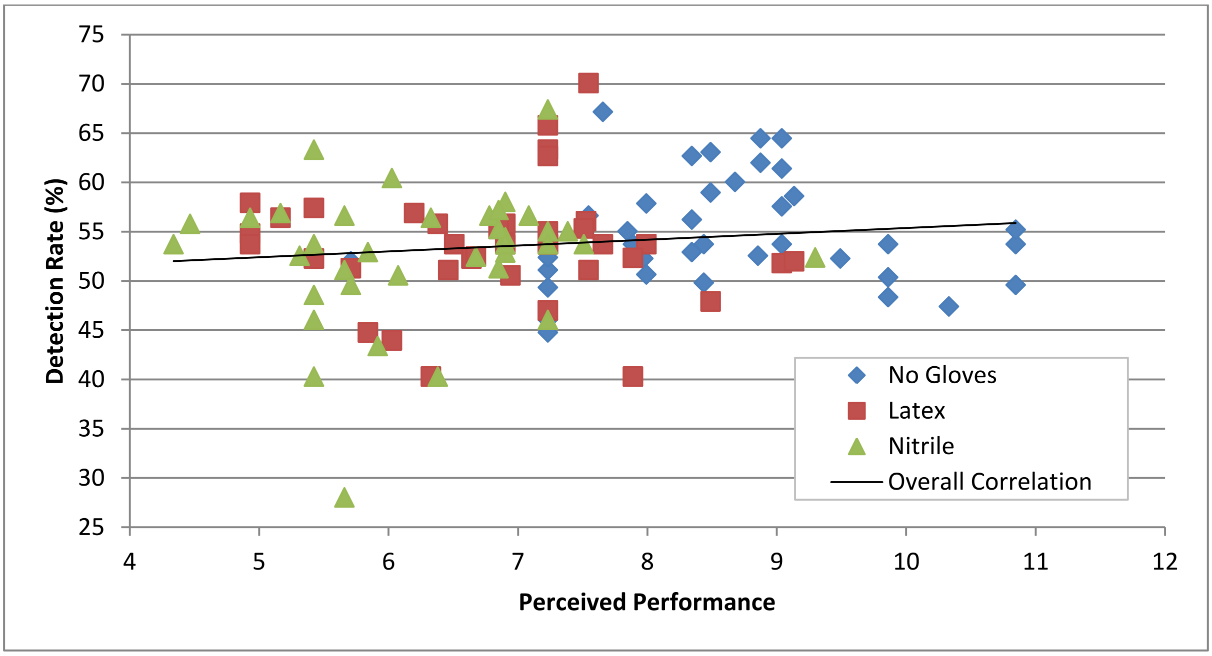


Figure 186. Relationship between detection rate and perceived performance in the SMETT 'Princess and the Pea' (normalised scores)

The average normalised objective and subjective scores for each hand condition are shown in Figure 187.

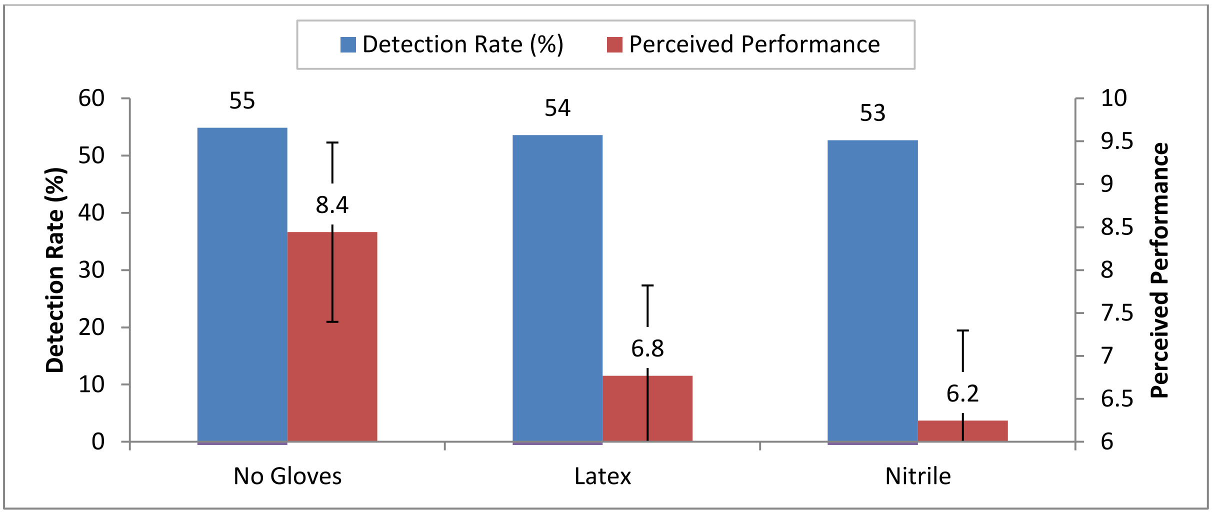


Figure 187. Average normalised objective and subjective scores for 39 subjects in three hand conditions in the SMETT 'Princess and the Pea' (with 95% confidence intervals for perceived performance)

None of the three datasets deviated significantly from a normal distribution. Paired t-tests again found the perceived difference between the ungloved conditions and the two gloved conditions to be significant ($p < 0.001$), but the difference between the gloved conditions was not statistically significant ($p = 0.058$). No significant differences had been found in the mean detection rate between hand conditions. This, combined with the lack of correlation of subjective and objective results, could suggest that the perceived differences were due purely to psychological reasons. However, the fact that the same trend between the three conditions emerged might also suggest that larger-scale testing or improvements in the test method could increase the significance of measured differences in performance.

10.3.3. Pulse Location Test

The relationship between perceived performance and score in the Pulse Location Test is shown in Figure 188. The Pearson's correlation analysis showed a moderate, positive correlation between the variables ($r = 0.591$, $N = 51$, $p < 0.001$).

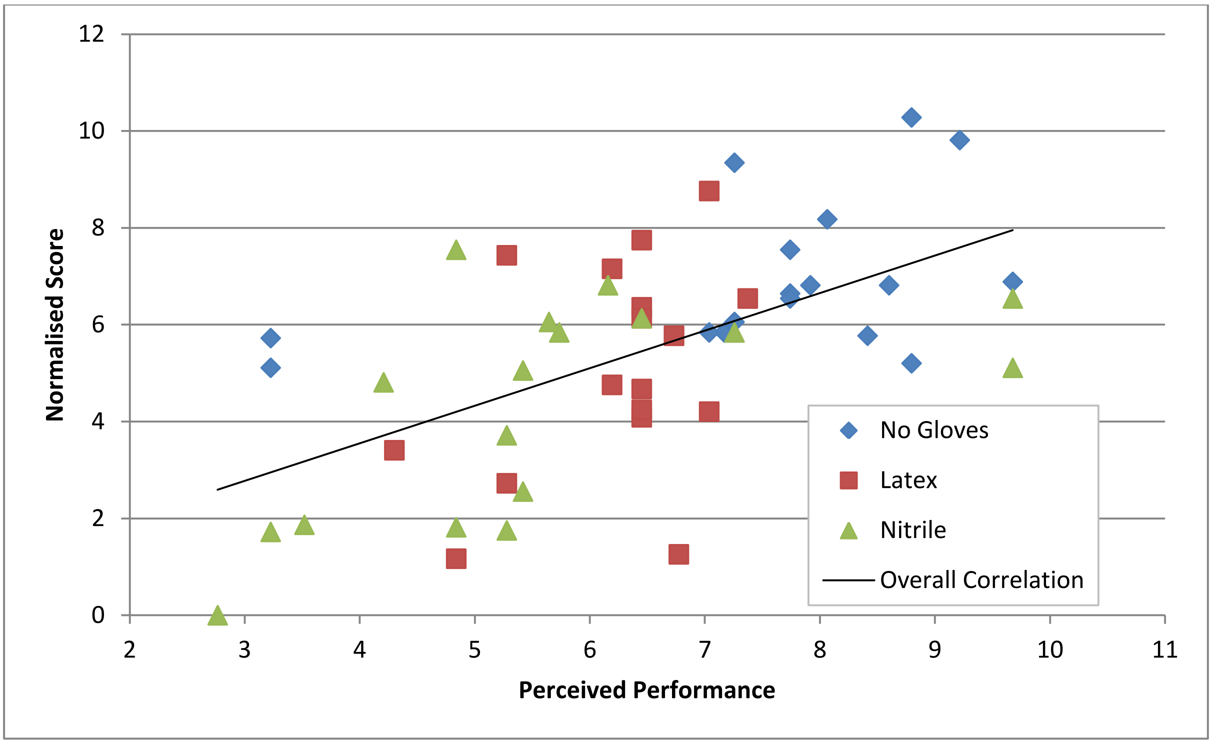


Figure 188. Relationship between score and perceived performance in the Pulse Location Test (normalised scores)

The average normalised objective and subjective scores for each hand condition are shown in Figure 189.

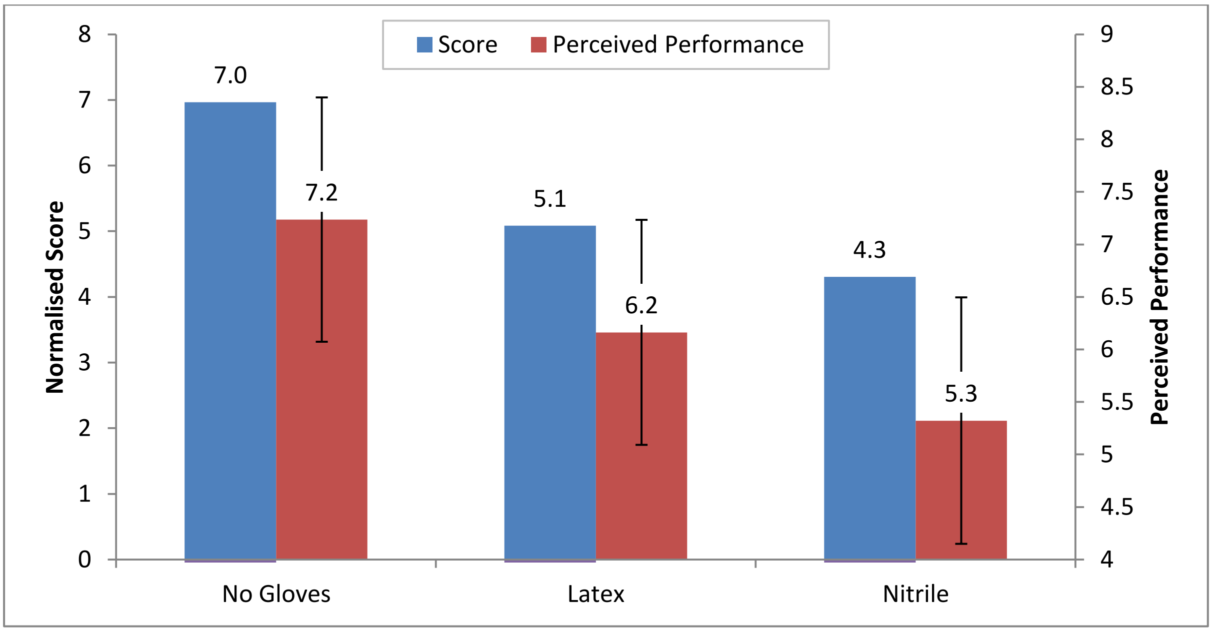


Figure 189. Average normalised objective and subjective scores for 17 subjects in three hand conditions in the Pulse Location Test (with 95% confidence intervals for perceived performance)

Two of the three datasets deviated significantly from normality ($p \leq 0.009$), so the non-parametric Wilcoxon Signed Ranks test was used to analyse the significance of differences. The results are shown in Table 49.

Table 49. Significance of paired differences in perceived performance in the Pulse Location Test

	Latex	Nitrile
No Gloves	NS (0.055)	S (0.038)
Latex		NS (0.276)

Only the ‘No Gloves’ and the ‘Nitrile’ perception scores were significantly different, although the *p* value between ‘No Gloves’ and ‘Latex’ scores was close to significance. The perception results compare well with the actual test scores, giving the same ranking of the three hand conditions, although the significance of the differences between the ungloved and gloved scores was greater in the objective results ($p \leq 0.021$), while the difference between the gloves was less significant ($p = 0.671$).

10.3.4. Suturing Test

The relationship between perceived performance and completion time in the suturing test is shown in Figure 190. The Pearson’s correlation analysis showed a weak, negative correlation between the variables ($r = -0.271$, $N = 54$, $p = 0.047$).

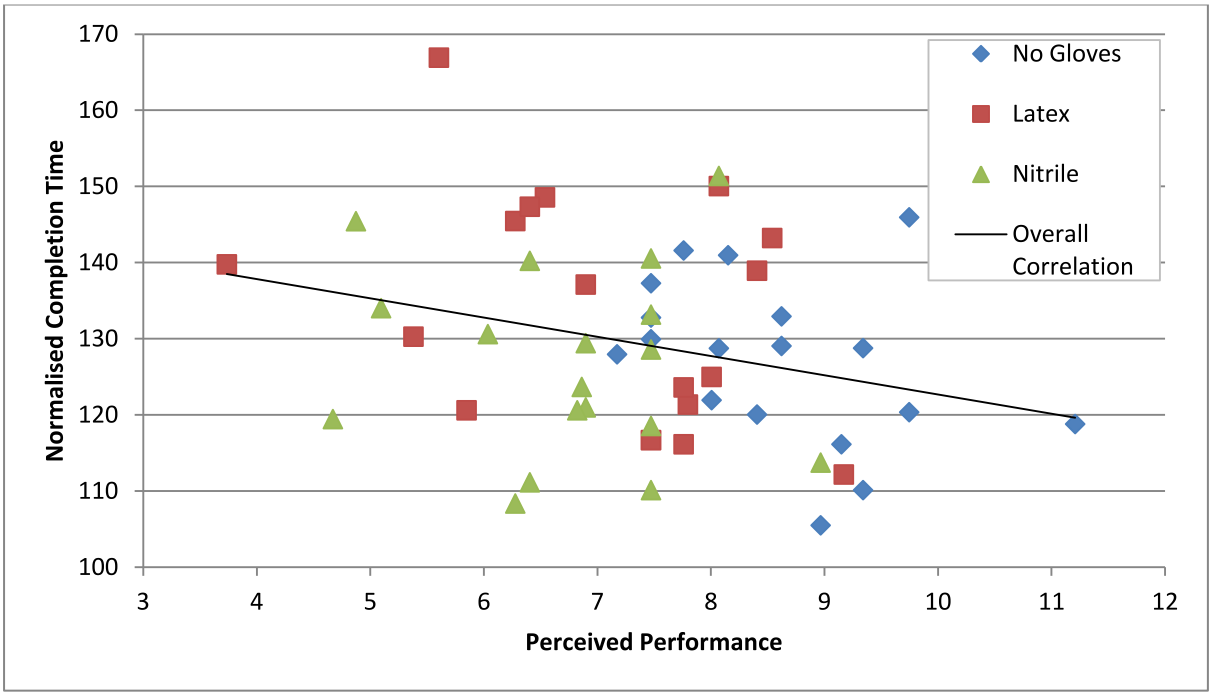


Figure 190. Relationship between completion time and perceived performance in the suturing test (normalised scores)

The average normalised objective and subjective scores for each hand condition are shown in Figure 191.

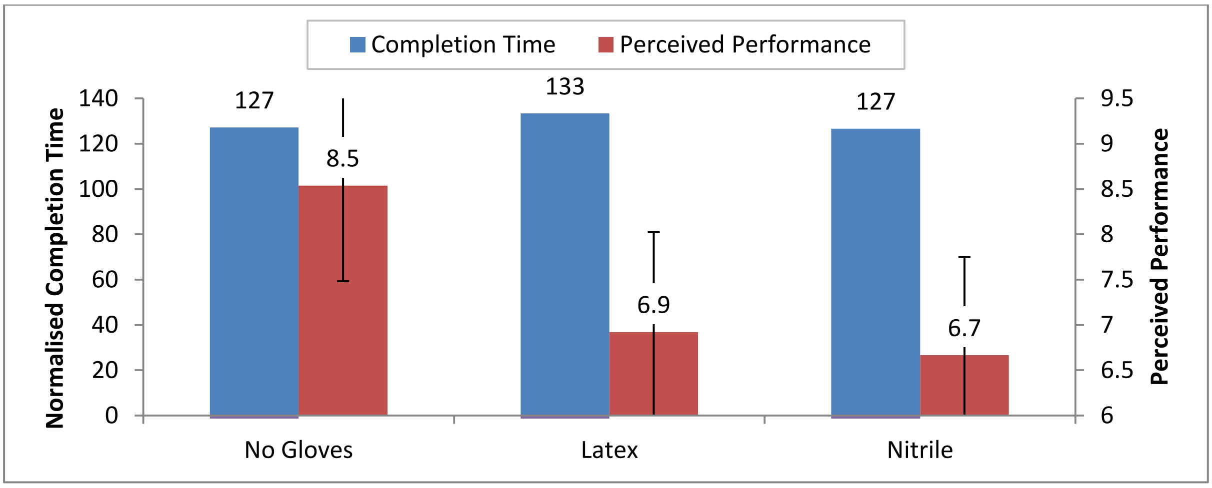


Figure 191. Average normalised objective and subjective scores for 18 subjects in three hand conditions in the suturing test (with 95% confidence intervals for perceived performance)

Only one of the datasets deviated significantly from normality ($p = 0.038$), so repeated measures t-tests were used to analyse the significance of differences between hand conditions. The perceived performance in both gloved conditions was significantly less than in the ungloved condition ($p \leq 0.009$), but the difference between the gloved conditions was not significant ($p = 0.345$). No significant differences were previously found between the completion times for the different hand conditions (Chapter 6) and performance was slower on average with latex gloves than without gloves.

10.3.5. Crawford Small Parts Dexterity Test

The relationship between perceived difficulty and combined score in the Crawford Small Parts Dexterity Test is shown in Figure 192. The Pearson's correlation analysis showed a weak, negative correlation between the variables ($r = -0.235$, $N = 100$, $p = 0.019$).

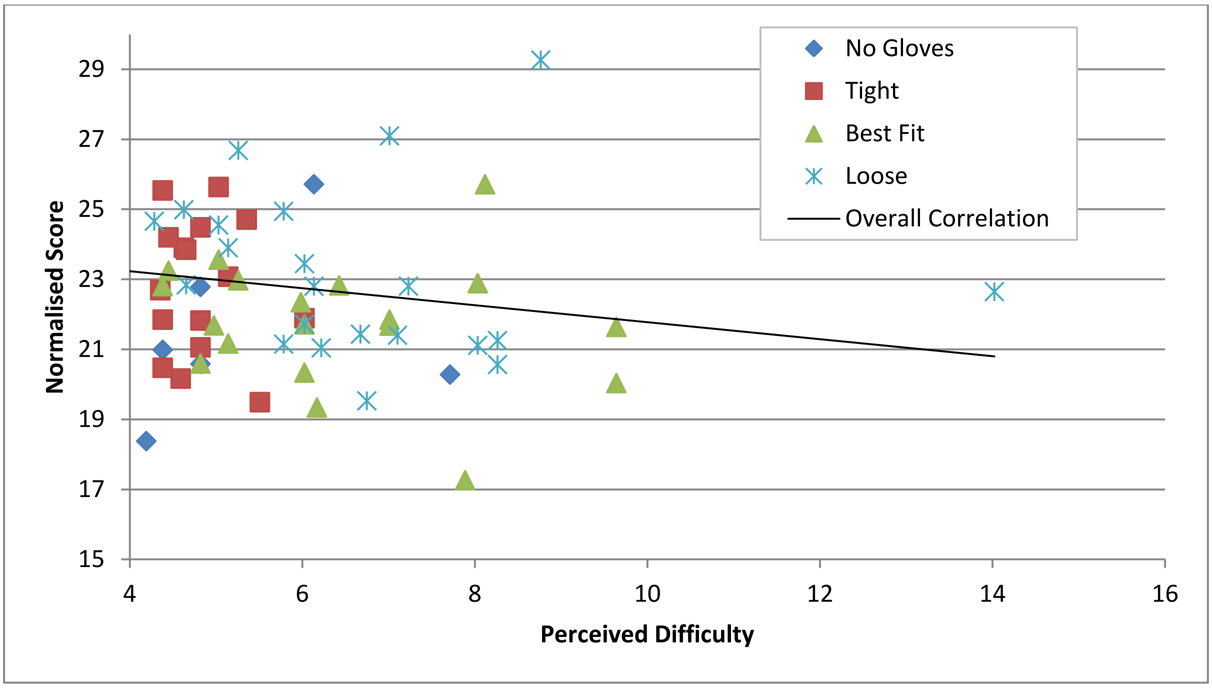


Figure 192. Relationship between combined score and perceived difficulty in the Crawford Small Parts Dexterity Test (normalised scores)

The average normalised scores and perceived difficulties for each hand condition are shown in Figure 193.

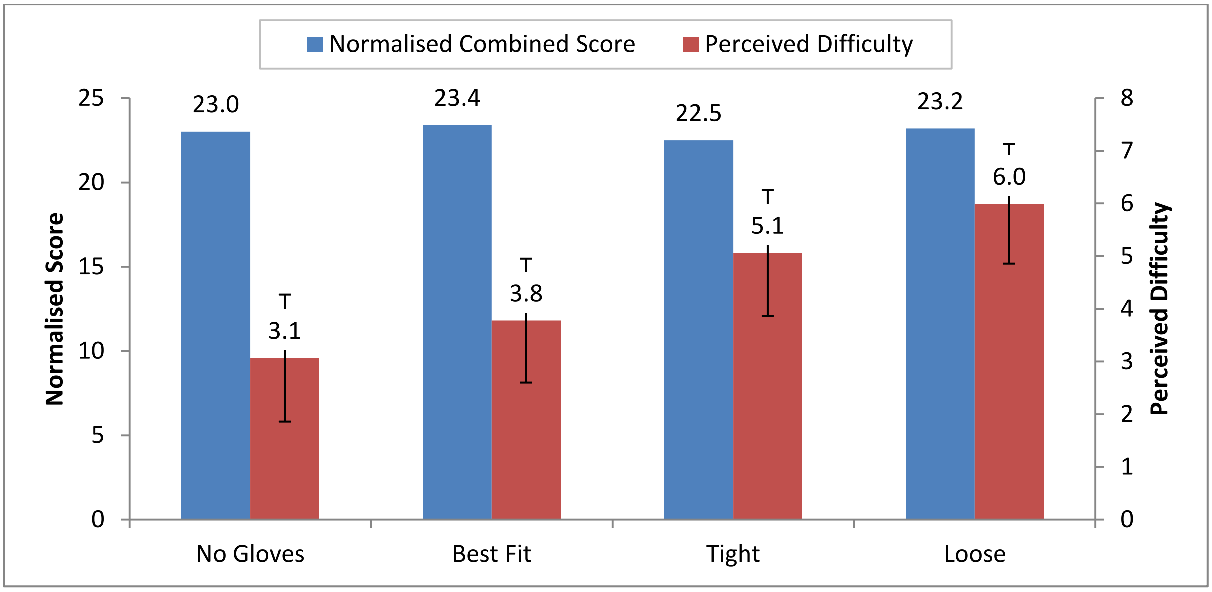


Figure 193. Average normalised score and perceived difficulty in the Crawford Small Parts Dexterity Test for 25 subjects in four hand conditions (with 95% confidence intervals for perceived performance)

Only one of the four datasets deviated significantly from normality, so paired-samples t-tests were used to analyse the significance of differences in perceived difficulty.

The results are shown in Table 50. Only the ‘Tight’ and ‘Loose’ hand conditions were not perceived to produce significantly different levels of difficulty in performing the Crawford SPDT (p = 0.229). However, no significant effect of hand condition on score was found in either the ‘Pins and Collars’ or the ‘Screws’ test, and the subjective and objective ratings do not follow a similar trend. In fact, a better average combined score was achieved with the loose gloves than without gloves, despite the perception that the test was almost twice as difficult with the loose gloves than ungloved.

Table 50. Paired t-test results for Crawford SPDT perceived difficulty

	Best Fit	Tight	Loose
No Gloves	S (0.031)	S (0.003)	S (0.000)
Best Fit		S (0.046)	S (0.001)
Tight			NS (0.138)

10.3.6. Bennett Hand-Tool Dexterity Test

The relationship between perceived difficulty and completion time for the Bennett Hand-Tool Dexterity Test is shown in Figure 194. The Pearson's correlation analysis showed a very weak, positive correlation between the variables (r = 0.050, N = 100, p = 0.624).

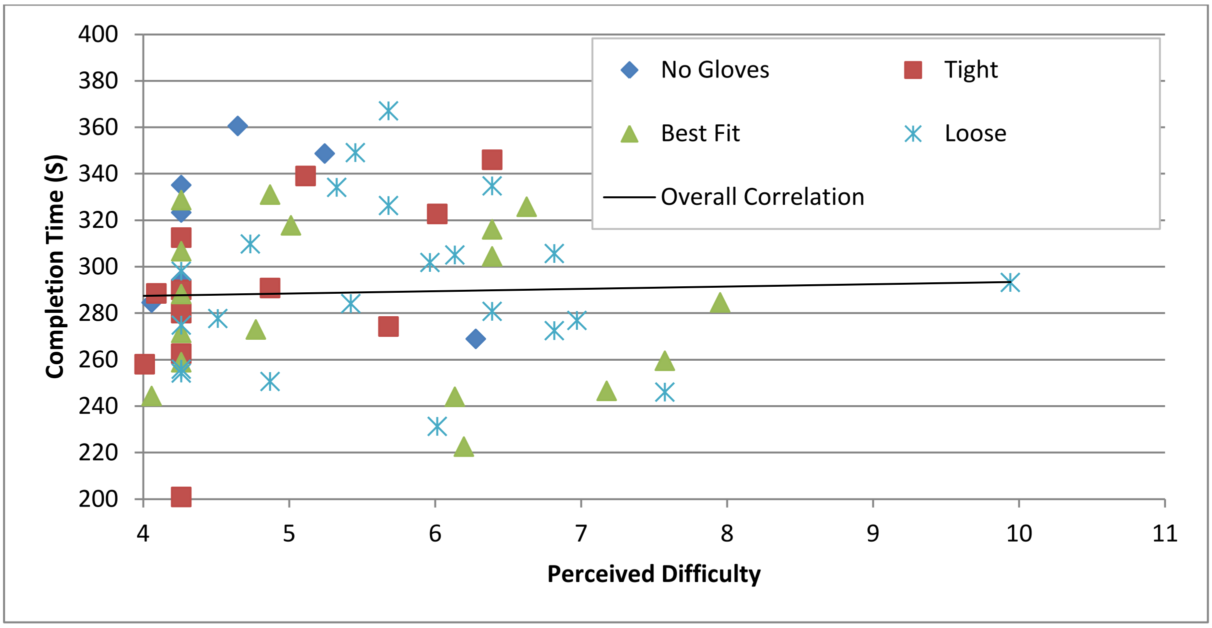


Figure 194. Relationship between completion time and perceived difficulty in the Bennett Hand-Tool Dexterity Test (normalised scores)

The average normalised scores and perceived difficulties for each hand condition are shown in Figure 195.

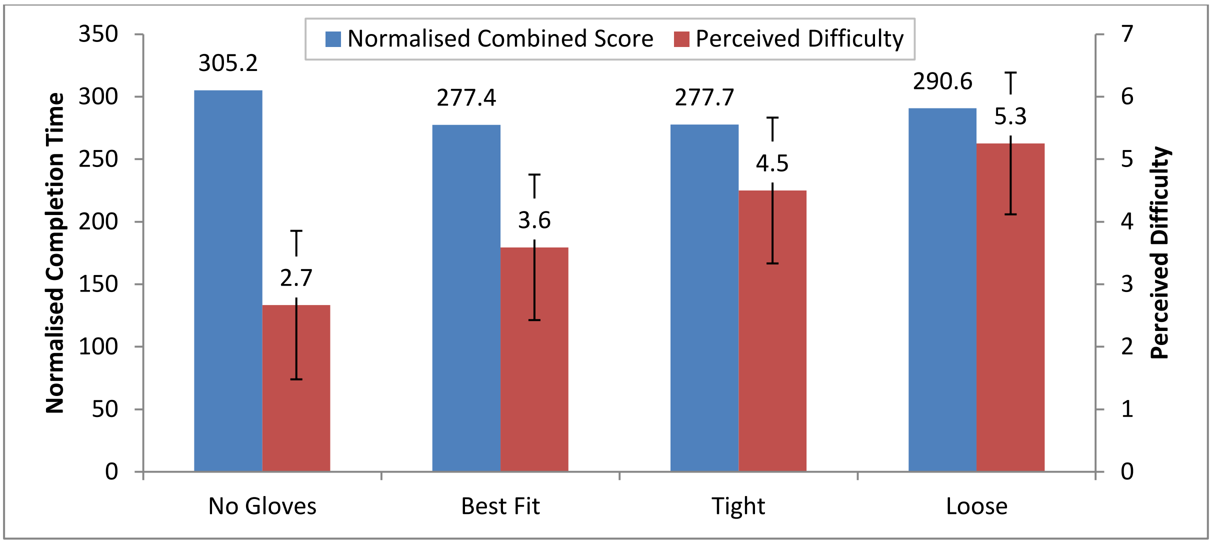


Figure 195. Average normalised completion time and perceived difficulty in the Bennett Hand-Tool Dexterity Test for 25 subjects in four hand conditions (with 95% confidence intervals for perceived performance)

Three of the four datasets deviated significantly from normality, so the Wilcoxon Signed Ranks test was used. The results are shown in Table 51.

Table 51. Wilcoxon Signed Ranks results for Bennett H-TDT perceived difficulty

	Best Fit	Tight	Loose
No Gloves	S (0.012)	S (0.001)	S (0.001)
Best Fit		NS (0.155)	S (0.001)
Tight			NS (0.138)

Only the differences in perceived difficulty between the ‘Tight’ condition and the other two gloved conditions were not significant, whereas there were no significant differences in completion time between the gloved conditions, and the ‘No Gloves’ condition performed worst, despite being rated the easiest.

The results suggest that the level of difficulty perceived by participants in this test was unrelated to their level of performance and that, while the differences may have been an indicator of discomfort or increased concentration, they did not affect the short-term performance of the task.

10.4. Discussion

In general, there was good agreement between the perceived and measured performance for the tactility tests, but not for the dexterity tests, in which hand condition did not generally have a significant effect on measured performance.

The only significant difference found in measured performance in the three dexterity tests was that the Bennett H-TDT was actually performed significantly more slowly in the ungloved condition than in two of the gloved conditions, despite being perceived to be the least difficult. In fact, in all three dexterity tests, ungloved performance was perceived to be significantly better or less difficult than gloved performance but did not produce the best performance in any of them. In contrast, it did produce the best performance in all three tactility tests, as was perceived by the subjects.

The difference in ability to perceive performance could be an artefact of the test methods, in that it is generally easier for the subject to estimate detection rate than completion time, although the same logic cannot be applied to the Crawford test, in which Tasron [160] measured completed assemblies or screws in a given time. A more likely explanation in the case of Tasron's tests is that they were always performed first in the ungloved condition, and since no practice had been allowed, subjects would tend to perform worst in the first test. Perception of difficulty may have picked up finer details such as differences in the level of friction or tactility, which were counteracted by a general slowness in performing the task as subjects got to grips with it. It is generally accepted that dexterity tests need to be performed multiple times (e.g. [6] where the 21st to 30th tests were taken) to remove learning behaviour before comparing test scores. The differences in perceived difficulty might indicate effects that would then emerge as measurable differences. However, until such testing is carried out, this hypothesis cannot be proved.

The perceived differences in difficulty may also indicate levels of comfort which might be inducing stress or fatigue. Tasron also recorded perceived levels of fatigue, and Pearson's correlation analysis showed a moderate correlation between perceived difficulty and fatigue (0.482, $N = 100$, $p < 0.001$).

In the case of the suturing test, in which the subjects were experienced medical practitioners, greater influence of preconceptions about glove performance could be expected. While there were no significant differences between latex and nitrile in either the measured or perceived performance (perhaps due to the small sample size), the average perceived performance of latex was higher than nitrile, despite the completion time being slower. This could either indicate increased levels of stress with the nitrile that did not immediately affect performance, or could be a result of preconceptions that latex are better. These preconceptions could themselves be influenced by the opinions of other practitioners, or may indicate other performance differences that were not measured, such as a difference in wet grip (e.g. [145]), which was mentioned by some practitioners during the testing. Performing the suturing task in more realistic lubrication conditions (e.g. fat, blood) would be worthwhile to ascertain whether real differences exist.

10.5. Conclusions

Perceived performance, as scored by subjects using magnitude estimation, was found to be in good agreement with measured performance in the tactility tests, but not so in the dexterity tests. Reasons suggested for this were: differences in test methods, with some being easier to estimate performance in than others; the effect of learning behaviour, giving reduced performance in the ungloved condition that was not perceived; preconceptions, particularly for medical practitioners, about the relative performance of latex and nitrile; or there may have been genuine differences in difficulty that were masked by subjects' ability to adapt. These differences may emerge as heightened stress or fatigue levels and might affect longer-term performance, such as in a surgical operation lasting a number of hours. Further study should include measurement of stress and fatigue levels. It was also stated by some practitioners that performance differences were more evident in wet conditions, so lubricated testing of the suturing test, for example, might produce differences between gloves that matched what was perceived.

11. Physical Properties

11.1. Introduction

In order to understand the differences in perceived and actual performance between glove types, it is necessary to understand the physical differences between the gloves, including the material properties and glove thickness. Because physical properties and dimensions of medical gloves must conform to international standards [4, 5], equipment and standardised test methods were available at BM Polyco Ltd. for measurement of glove thickness and stress-strain characteristics.

11.2. Thickness measurements

The mean thickness of four types of medical glove (Finex® PF latex, Finite P Indigo AF nitrile, Finity PF vinyl and Biotex Plus latex surgical) was measured using a digital micrometer.

11.2.1. Procedure

Three gloves of each type were randomly selected. Three samples were cut from the smooth palmar/dorsal surface of each glove using a 3mm wide BN EN 455:2000 dumbbell cutting die. The thickness at the centre of each sample was measured using a digital micrometer (Sylvac). The mean thickness and 95% confidence interval for each glove are shown in Table 52.

11.2.2. Results

Table 52. Mean thickness of four types of medical glove

Thickness (µm)	Finex (Latex)	Indigo (Nitrile)	Finity (Vinyl)	Biotex Plus (Latex Surgical)
Mean	123	74.3	67.4	199
95% C.I.	3.9	4.0	1.7	4.3

The surgical glove was by far the thickest, perhaps because it is more likely to encounter sharp tools and open wounds. The latex examination glove was 66% thicker on average than the nitrile, while the vinyl was the thinnest.

11.3. Stress-strain characteristics

When comparing latex and nitrile gloves in the structured interviews (Chapter 4), many practitioners commented that the nitrile gloves were less ‘flexible’, ‘elastic’ or ‘conformable’, or did not fit as well as the latex. Similarly, observations were made about the inflexibility of the vinyl gloves. In order to test these assertions, samples of the four gloves used in Section 11.2 were tested on a tensometer (Instron Ltd.).

11.3.1. Procedure

Three samples were taken from each glove in the same way as described in Section 11.2. The test specimens were placed in the tensometer and clamped at either end. Markers were placed on the specimen at either end of the thin section. Video equipment was used to track the markers and calculate the extension. Once the video equipment had detected the markers, the tensometer motor was started, stretching the specimen at a rate of 500mm/min (as specified in [4]). Once the specimen had snapped, the motor stopped and the tensometer returned to its original position. The apparatus is shown in Figure 196. The results were recorded in a stress-strain graph by the software (Bluehill®, Instron Ltd.).

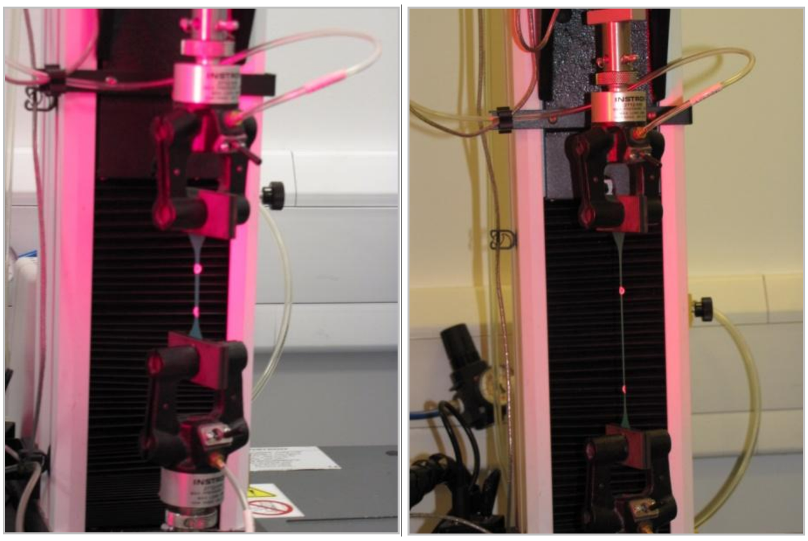


Figure 196. Tensile test apparatus

11.3.2. Results

The results printout from the software is shown in Figure 197, with the mean values for each glove at the recorded intervals of elongation shown in Figure 198. The mean tensile stress at 200% elongation is shown in Table 53.

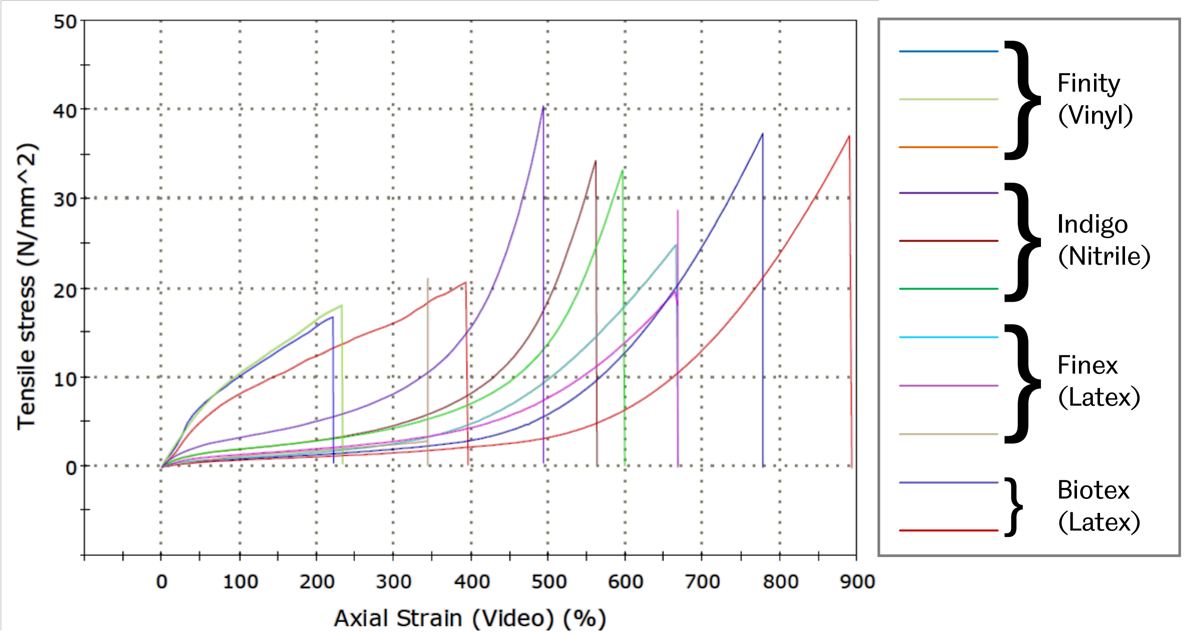


Figure 197. Stress-strain data for medical gloves

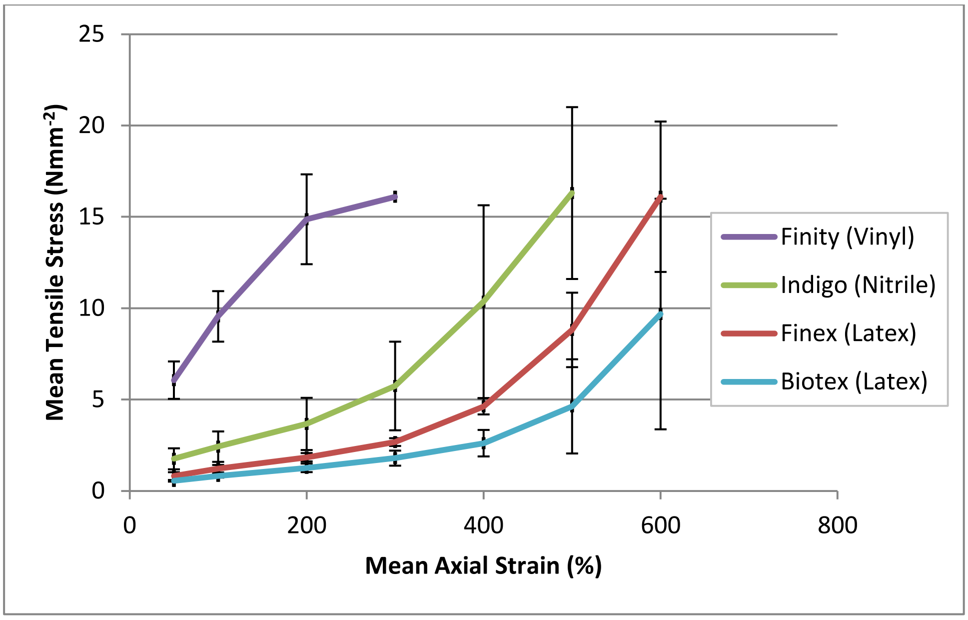


Figure 198. Elasticity of medical gloves (showing standard error)

Table 53. Tensile stress at 200% elongation for four medical glove types

Tensile stress (Nmm^{-2})	Finex (Latex)	Indigo (Nitrile)	Finity (Vinyl)	Biotex Plus (Latex Surgical)
Mean	1.84	3.66	14.9	1.26
95% C.I.	0.23	1.43	2.46	0.24

11.4. Tear strength

Since the primary purpose of medical gloves is to act as a barrier to infection, the integrity of the gloves is vital. The gloves often come into contact with sharp objects such as needles, scalpels, and bone fragments, and need to have some ability to resist tearing. While there are already standards defining minimum medical glove tear strength [4], it is of interest to know the relationship between glove thickness, tear strength and tactility, and whether an optimum value of thickness can be found.

11.4.1. Procedure

The tear strength of three types of examination glove was tested (Finex®, Indigo and Finity) in the “trouser tear test”. The procedure was similar to that used for the stress-strain testing, in that three samples were cut from each type of glove, placed in the tensometer and pulled until failure. However, rather than being a dumbbell shape, the sample had a cut in it and was pulled along the line of the cut as shown in Figure 199. The rate of strain was 100mm/min (as specified in [5]). The tensometer recorded the maximum applied force. The apparatus is shown in Figure 200.

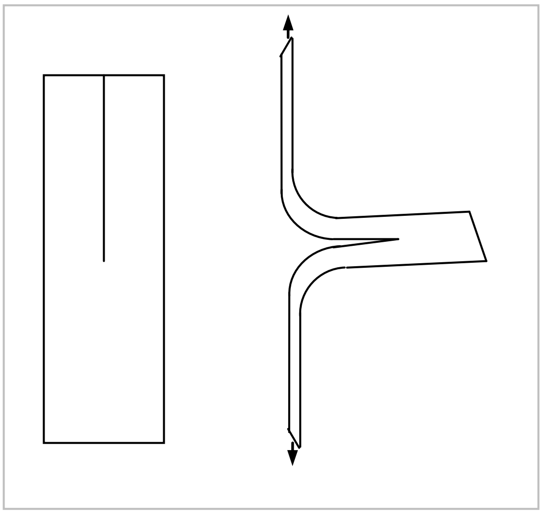


Figure 199. Tear strength test sample

Figure 200. Tear strength test apparatus

11.4.2. Results

The mean tear strength for each of the three glove types is shown in Table 54, with 95% confidence intervals.

Table 54. Tear strengths of three examination glove types

	Finex (Latex)	Indigo (Nitrile)	Finity (Vinyl)
Mean tear force (N)	2.90	0.64	0.48
95% C.I.	0.34	0.19	0.01
Tear strength (Nmm^{-1})	21.7	8.63	7.49

11.5. Discussion

The Finex® latex gloves were found to be almost twice as thick as the Indigo nitrile and Finity vinyl gloves. The results of the Semmes-Weinstein Monofilaments tests (Chapter 7), in which a double layer of gloves significantly increased the pressure threshold, suggested that glove thickness and tactility were negatively correlated. However, in the same test, the Finity vinyl and Finex® latex gloves performed very similarly, with the vinyl having a slightly higher mean threshold, despite being almost half the thickness. The nitrile performed better than the latex in the more dynamic SMETT 'Bumps' ($p = 0.065$ in the most sensitive range).

While these results do not show a clear relationship between thickness and tactility, there are other factors, such as the material stiffness (Section 11.3), which may affect the way tactile information is transmitted through the glove.

As expected, the vinyl glove was by far the stiffest and failed at the lowest strain, with the nitrile being stiffer than the latex, and the surgical glove being the most elastic. This confirms what was perceived by medical practitioners in the interviews, and explains why latex gloves appear to conform better to the hand.

The latex gloves had the highest tear strength, and the vinyl had the lowest, even when calculated per unit thickness. The values correspond well with those quoted in [53] (21 and 4.7 Nmm^{-1} for latex and vinyl respectively). Given the significant differences in tear strength, the fact that the vinyl gloves are half the thickness of the latex ones seems strange, although the strength requirements are much less stringent for vinyl than latex [4]. The relationship between tear strength and tactility will be considered further in Chapter 12.

11.6. Conclusions

Of the three PolycoHEALTHCARE examination glove types tested in this study, the Finex® latex gloves were the thickest, but also had the greatest material tear strength and highest elasticity. The Finity vinyl gloves were the thinnest and stiffest, and had the lowest material tear strength. Analysis of tactility test results suggested that both thickness and material properties are factors in the tactile performance of medical gloves.

12. Analysis and Discussion

12.1. Linking glove properties to performance

The ultimate aim of this work is to enable the design of medical gloves that allow the best possible performance of medical tasks. In order to do this, we first need a battery of tests by which performance can be objectively measured. Based on information gathered from practitioners, the research was focused on three areas of performance: grip and friction, dexterity and tactility. Through the selected tests, we then need to understand how glove properties relate to performance in each of the three areas, and whether there are conflicting requirements where compromises must be made.

It may also be that the requirements are not the same for all practitioners, with some tasks requiring greater dexterity, some requiring tactility, and some situations primarily requiring an effective barrier to infection. Already, with a range of glove thicknesses and materials available and the ability to "double glove", the preferences of different specialities can be seen: orthopaedic surgeons, for example, use a double layer with a green indicator glove to ensure punctures are quickly spotted, while ophthalmologists generally use thin, high-friction microsurgery gloves to ensure the greatest dexterity. However, these preferences are based on experience, rather than a full understanding of how each of the glove properties contributes to performance. In this chapter, the results of the experiments in the current study are analysed to determine what can be concluded about the relationship between glove properties (material, thickness, surface finish, fit) and performance (dexterity, tactility, grip).

12.1.1. Glove material

Five glove materials have been included in various experiments in this study: natural rubber latex (“latex”), polyvinyl chloride (“vinyl”), acrylonitrile butadiene (“nitrile”), polychloroprene (“neoprene”) and synthetic polyisoprene (latex is naturally-occurring polyisoprene), but others are also available.

The main comparison made in this study was between nitrile and latex, since latex examination gloves have been replaced in recent years by nitrile in almost all NHS Trusts, due to fears about latex allergy. In structured interviews (Chapter 4), almost half of participants expressed a preference for latex over nitrile (none expressing a preference for nitrile except for reasons of allergy). The main reasons given were the better fit, elasticity and tactility of latex gloves. Practitioners also perceived performance with latex gloves in dexterity and tactility to be slightly, though not significantly, better than nitrile.

Due to a shortage of nitrile gloves at the time of testing, the dexterity testing compared latex and vinyl gloves. Only the Crawford ‘Screws’ test found a significant difference in performance, with completion times significantly faster with vinyl than with latex, and in two of the other three tests, vinyl also out-performed latex, though the differences were not statistically significant.

The results agree fairly well with previous findings. Studies using the Purdue Pegboard [53, 67] had not found significant differences in dexterity between latex and vinyl, but found performance was significantly better with latex than with nitrile. In medical task simulations [53, 83] the results were similar, with latex outperforming nitrile and vinyl in one study, and latex and vinyl varying in ranking across the tests in the other.

In the tactility tests, no significant differences in performance were found between glove types. Latex performed better than vinyl in the Semmes-Weinstein Monofilaments test, and better than nitrile in four others, but in the test with the most significant difference, the SMETT 'Bumps', 25% more bumps were detected in the critical region with the nitrile gloves than the latex.

Previous studies [64, 73, 75, 77] had also found no differences in the effect on performance in the Semmes-Weinstein Monofilaments test or on roughness discrimination between glove materials, but performance in the 'sponge and glue' test [53] was significantly better with latex gloves than with vinyl. Since the glove thicknesses are not known, it is difficult to explain both the 'sponge and glue' and the SMETT 'Bumps' results with a single theory.

In the grasping and friction tests, the results were less clear. Dynamic tests with the Sheffield rig gave the most significant differences, and found latex to have the highest coefficient of friction with steel in the dry, followed by nitrile, with vinyl having the lowest. However, one test found nitrile to have the highest friction in the wet, while the other found latex to have the highest.

The fact that vinyl was generally found to have the lowest friction could explain the fact that it performed better in most of the dexterity tests than latex, particularly the Crawford 'Screws' test, which requires use of a screwdriver, in which there is constant movement of the glove on the screwdriver surface. This is supported by some subjects' comments that the latex stuck to the screwdriver and hindered movement, and that pins sometimes stuck to the glove in the Purdue test. It is therefore clear that high friction is not always desirable. To remove the effects of other glove properties such as elasticity, further investigation of friction effects on dexterity should use friction modifiers on identical gloves.

It is difficult to make a fair comparison between the materials based on the above experiments alone, since the three examination glove types also varied in dimensions, thickness, grip pattern and surface finish. The Finity vinyl gloves were the thinnest at 67μm, followed by the Indigo nitrile at 74μm, with the Finex® latex gloves being the thickest at 123μm, almost twice as thick as the vinyl. The Indigo gloves had a grip pattern on the fingertips (Figure 14) that was not present in the others, while the latex gloves were chlorinated on the outer surface, giving a rough finish.

It is not clear why the latex gloves are thicker than the other two, despite having greater material tear strength. It is possible that the lack of differences found in tactility between latex and nitrile, despite anecdotal evidence to the contrary, could be due to this difference in thickness in the PolycoHEALTHCARE gloves. This will be explored further in the next section.

In terms of physical properties, latex was found to be significantly more elastic than nitrile, as expected, and both were significantly more elastic than vinyl. It was expected that the most elastic glove, conforming best to the hand, would provide the least reduction in dexterity. However, the frictional properties are also clearly important and the lower friction of the vinyl may have countered the effects of the poorer conformity to the hand in some tests more than others. In comparing materials, the two properties cannot easily be separated. The effect of the lack of elasticity in the vinyl gloves might be clearer with less well-fitting gloves, where loose material will be more of a hindrance to dexterity. This is an important issue to investigate, as a number of practitioners stated that they were often unable to obtain their preferred glove size in clinical situations.

It was also expected that the most elastic gloves would transmit tactile signals most effectively, acting more like a “second skin”. Given the dimensional and other differences in the gloves used in the current study, this hypothesis has not been proved. Future work should include production and testing of gloves that are identical in every aspect (as far as possible) except the material, in order to make a true assessment of the effect of material on performance.

12.1.2. Glove thickness

Although direct comparisons cannot be made between otherwise-identical single-layer gloves of varying thicknesses, some of the dexterity and tactility tests were performed with both a single and a double layer of latex gloves of identical size. Without exception, the subjects performed worse with a double layer than a single layer. In the Semmes-Weinstein Monofilaments and the finger dexterity tests, that difference was significant, but in the tool dexterity tests it was not. The hand dexterity tests require accurate tactile feedback to manipulate the pins without dropping them, which may not be as vital in tweezer and screwdriver dexterity.

“Double gloving” obviously introduces other issues that are not present with a single, thicker layer, such as the slip between layers and the resulting distortion of tactile signals, but in the Semmes-Weinstein Monofilaments test, performed on a taut, flat fingertip, these differences may be less of an issue. We can say fairly confidently that the increased thickness reduces *cutaneous sensibility*.

This fits well with the findings of previous research. Shih et al. [56] found that increasing the number of layers of latex examination gloves increased the Semmes-Weinstein threshold, while reducing dexterity. Kopka et al. [73] tested two latex gloves of different thicknesses, and found that subjects had a lower threshold with the thinner glove. Nelson and Mital [64] actually produced their own latex gloves of varying thickness, and found no significant effect of thickness on tool dexterity or on tactility, although their test methods were fairly coarse. Pourmoghani [65] used three thicknesses of latex gloves in standard finger dexterity tests, and found a significant effect of glove thickness (thickness and score being negatively correlated).

The effect of glove thickness on tactility, and hence on dexterity, is fairly clear, both from the current study, and from previous research. Thicker gloves reduce the ability to sense tactile cues, and this reduces the ability to manipulate objects, most probably because of the inability to perceive the beginning of slip and therefore make appropriate adjustments to grasp force. It would certainly be worthwhile comparing gloves of varying thicknesses (all else being equal) with the pinch grip apparatus, to determine what effect, if any, the glove thickness has on grasping forces and the ability to perceive slip.

In terms of glove design, the immediate answer appears to be “the thinner, the better” in order to optimise performance. However, glove thickness also has an effect on puncture and tear resistance, which are fundamental to the purpose of medical gloves in providing a barrier to infection.

12.1.3. Tear resistance vs. tactility

Minimum tear strengths for gloves are already covered by international standards [5], and standard tests exist. However, it has been found that the requirements of all practitioners are not the same in terms of the importance they place on tear resistance and tactility. Orthopaedic surgeons almost always use a double layer of gloves, and sometimes even Kevlar® ones, because they are regularly exposed to sharp objects and mostly require only gross dexterity; microsurgeons such as ophthalmologists will wear gloves that are thinner than the standard, to allow minute control over instruments, because they run much less risk of puncturing the gloves. It seems necessary, therefore, to retain a range of gloves with different levels of emphasis on tactility or puncture resistance, in order to meet the requirements of the whole range of medical practitioners.

In general, increasing the thickness of the gloves will increase tear and puncture resistance (e.g. [64]) and reduce tactility. However, the material properties can also be changed, and it has been shown that there are large variations in tear strength between latex, nitrile and vinyl. Since the thickness of the gloves seems to have a much greater effect on tactility and dexterity than do the material properties, improving the tear strength of the glove material could allow thinner gloves to be produced that would meet the tear strength requirements, but increase the tactility and dexterity to a level more comparable with ungloved hands. It is recommended that further development of medical gloves focuses on this aspect.

12.1.4. Glove fit

The effect of glove fit on performance has been extensively analysed in Chapter 9. It was found that, in general, glove fit had a greater effect on dexterity than tactility, and that, while overly-tight gloves had the biggest effect on tactility, overly-loose gloves had the greatest effect on dexterity. More crude comparisons can be made from the earlier tests (Test Battery 1) in which larger latex gloves were tested alongside those chosen as the best fit. The larger gloves performed significantly worse than "Best Fit" gloves in both the Purdue Pegboard tests, but there were no significant differences in the Crawford tests or the Semmes-Weinstein Monofilaments.

The result supports the hypothesis that loose gloves have more of an effect on dexterity than tactility. The static nature of the 'Pins and Collars' test means that the extra material was unlikely to significantly affect performance. However, the 'Screws' result is surprising, given the complaints that the loose material wrapped around the screwdriver. The loose gloves did perform worse than "Best Fit" in both the author's and Tasron's [160] 'Screws' tests, and the lack of significance may have been an artefact of the small sample size. Three previous studies [61, 67, 98] that analysed the effect of glove fit on dexterity agreed that over-sized gloves cause a reduction in dexterity.

To gain a fuller picture of which dimensions are most significant to performance and what value or range of ease in each dimension will produce the optimum performance, testing on a much larger sample is required. However, given the deliberately coarse nature of the current examination glove sizing system, the number of available sizes being dictated by cost, it may be that this area is not the primary focus of future research.

12.2. What tests are needed to get an accurate picture of glove performance?

The definition of glove performance has been limited in this study to grip and friction, dexterity and tactility. While dexterity and tactility are fairly well defined in terms of good and bad performance, grip and friction are less clear. In some tasks, low friction is preferable; while in others, high friction may be required. The mechanism of grasping is also inherent in most forms of dexterity, and tactility is also linked to both the other two, in terms of feedback when grasping and manipulating.

Studying the effect of gloves on performance can take two forms. The tests at the applied end of the spectrum, that closely simulate medical tasks, can be used to give an indication of whether an existing or newly-designed glove will perform well in a given medical task, or a range of tasks covered by a representative test. In this case, the primary criteria for the test are that it is an accurate simulation of a real medical task or range of tasks, that it identifies whether glove properties have a substantial effect on clinical performance, and that, where meaningful differences exist, it discriminates sufficiently between “good” and “bad” gloves so that practitioners are supplied with the best available equipment. In order to reliably discriminate between gloves, the test will need to be accurate and repeatable.

The second form of study seeks to understand the mechanisms behind glove performance and define glove properties that will produce the best performance. In the long-term, both forms of study need to be combined. Without real understanding of the mechanisms and properties that contribute to glove performance, the testing process will merely be a form of trial and improvement, in which multiple configurations of material, thickness, surface finish and size are thrown at a battery of tests, and without realistic simulations of medical tasks, it will be impossible to determine whether differences found in the laboratory are relevant to clinical performance. With greater understanding of the relationship between properties and performance, this development process can be much more streamlined to focus on the areas where significant improvements can be made.

A summary of the findings from the analysis of test methods carried out in the study is shown in Table 55. In terms of dexterity tests, the most applied test, the **suturing test**, did not show any significant differences in performance between gloves. However, it has a clear similarity with a real-life task that was identified as a challenge for practitioners. In order to determine the reason for this lack of difference, and to further explore the effects of gloves on this kind of dexterity, further development of the test may be worthwhile, using hand suturing and including lubrication. The best results in terms of discrimination were achieved with the **Purdue Assembly** test and the **Crawford 'Screws'** test. Between them, these two cover finger and tool dexterity, and simulate a number of dextrous medical tasks such as placing dental crowns, inserting grub screws and plating fractures in orthopaedics.

Of the tactility tests, the most successful in discriminating between the gloves was the **SMETT 'Bumps'**. Some issues were identified with the manufacturing and the testing procedure, which may need to be explored in further detail in order to have full confidence in the test and to increase the significance of the results.

The **Pulse Location Test** and **Roughness Perception Test** also showed an ability to discriminate between hand conditions, but require some improvements to the apparatus and method. In order to provide a benchmark for future glove evaluation, a repeatable measure of pulse pressure is required in the Pulse Location Test, as well as professional manufacture of the equipment to avoid leaks. The range of roughness values in the Roughness Perception Test needs to be calibrated, since much larger differences in performance were found with the more coarse sandpapers.

The **Semmes-Weinstein Monofilaments**, on the other hand, are an established test for *cutaneous sensibility*, and showed good discrimination between ungloved and gloved tactility and between single and double layers of gloves. However, the resolution was not enough to discriminate reliably between glove types. A custom-made test based on the same principle, but using a continuous scale, and with some other minor adjustments, could be developed that would improve the accuracy and resolution of the test.

The four tests measure different types of tactility (spatial and vibratory) and include both applied (Pulse Location Test, SMETT 'Bumps') and theoretical (Roughness Perception Test and Semmes-Weinstein Monofilaments) tests. Between them, they represent a fairly comprehensive measure of glove effects on tactility.

The question of what tests are required to define glove friction and its effect on grasping is much less clear. All of the methods used had advantages and drawbacks. Ultimately, what is required is an accurate, repeatable test that simulates real frictional forces experienced in grasping. This means that static friction tests are preferable to dynamic ones, and that some representation of the elastic properties of the fingers is also necessary. However, there are still a number of issues to be worked through in both the **Pinch Grip** apparatus and the **Anthropomorphic Device for Simulating Hand-Object Interactions (ADSHOI)**. Further research needs to focus on the effects of lubrication, where larger and more consistent differences between the gloves may emerge, based on the testimonial evidence of surgeons. Theoretical tests using, for example, a goniometer to measure hydrophilicity (the ability of water to wet a surface) may also reveal important information about the behaviour of different gloves in wet conditions.

Table 55. Summary of test method analysis

Test Method	**Status**	**Comments**
Dexterity		
Purdue Pegboard Test	Existing	'Combined' dexterity is included in 'Assembly' and therefore redundant. Scoring is relatively coarse – requires large sample.
Crawford SPDT	Existing	'Pins and Collars' did not find an effect of hand condition, but 'Screws' showed some discrimination between gloves.
Bennett H-TDT	Existing	Results indicated that hand condition had a significant effect, that gloves improved performance, but learning behaviour also had an effect. Not thought to be good measure of glove performance.
Suturing Test	New	Did not find significant effect of hand condition. Improvements in method and larger sample size recommended.
Tactility		
S-W Monofilaments	Existing	Ungloved performance significantly better than gloved; double-gloving significantly reduced performance. No differences found between single-layer gloves.
Roughness Perception	Modified	Ungloved performance significantly better than gloved. Both spatial and vibratory coding affected by gloves, but differences between gloves were clearer with larger particles, where spatial coding dominated.
SMETT 'Bumps'	New	Ungloved performance significantly better than gloved. Produced by far the largest statistical differences between gloves of the tactility tests, although not significant with the sample size used.
SMETT 'P&P'	New	No significant effect of hand condition found.
Pulse Location Test	New	Ungloved performance significantly better than gloved, but no significant differences between gloves.
Dental Probe Test	Modified	No significant effect of hand condition found.
Grip and Friction		
Sheffield Finger Friction	Existing	Requires modification to produce accurate and repeatable friction measurements.
Polyco Friction Angle	Existing	Requires modification to produce accurate and repeatable friction measurements.
JAMAR Dynamometer	Existing	Grip strength not significantly affected by medical gloves.
Pinch Grip Rig	Modified	Results inconclusive – further development and larger-scale testing recommended.

13. Conclusions

13.1. The importance of the results for glove design

There is little or no evidence in the available literature that the medical glove design process includes any evaluation of the effect of gloves on users' manual performance. The phasing out of latex products in clinical environments, as well as the drive for lower costs, has meant that effect on manual performance has apparently not been a significant factor in procurement decisions. However, interviews with practitioners (Chapter 4) showed that many users had strong opinions about the effect of gloves on their performance and felt that their current gloves were less than optimal in this regard. Manual performance clearly has implications for the safety of both patients and practitioners; a reduction in dexterity can lead to an increase in slips and drops, while a reduction in tactility can lead to missed diagnoses or a tendency to remove gloves and thus increase infection risk.

The primary aim of the study was to "develop a suite of tests by which the performance of medical gloves could be measured, in order to improve the design process and enable production of medical gloves that allow practitioners to perform tasks as effectively as possible." Following a review of the available tests (Chapter 3) and a survey of the most relevant medical tasks (Chapter 4), a number of existing tests were recommended for further development and validation with medical gloves, and a number of new tests were proposed. The test apparatus and methods were then designed, refined and validated with small groups of participants (Chapters 6-8), allowing recommendations to be made (Chapter 12) for a battery of realistic, repeatable tests by which medical glove performance can be comprehensively characterised. Such tests enable consistent comparison of existing and new glove designs and the optimisation of materials, surface finishes, thickness and sizing so as to give the user the best performance in any given task. Any new design can be tested against benchmarks in dexterity, tactility and frictional properties for existing market leaders. Because the range of manual tasks included within medical practice varies so widely (from intricate eye surgery to hip replacement) it may be that a range of glove designs is needed to optimise performance across the board.

The new tests developed are particularly useful in characterising areas of manual performance that have not been well defined. While numerous dexterity tests have been available for many years, there has been little in the way of applied tactility tests. The SMETT ‘Bumps’ and ‘Princess and the Pea’ tests particularly have wider applications outside of glove testing, such as in the rehabilitation of neurological injuries. The Pulse Location Test and Suturing Test provide good simulations of common medical procedures that give a greater confidence of actual medical performance than less applied tests such as pegboards and monofilaments. There is still much development to be done in the area of grip and friction testing, but the apparatus and methods developed provide a basis for future research.

Although there was insufficient scope in the study to make definitive statements about the relationships between glove properties and performance (Chapter 12), the initial findings provide a focus for further research and development. The differences in thickness and fit, as well as material, between the PolycoHEALTHCARE gloves meant that distinguishing the effects of any one variable was difficult. Bespoke production of gloves that are, as far as possible, identical except in one respect will enable the effects of each variable to be more clearly seen. However, the results suggest that glove thickness is a significant factor in performance, particularly in tactility, with thinner gloves giving better tactility, and that glove fit also has an effect on both tactility and dexterity, although there may be an acceptable band of 'ease' (the difference between glove and hand dimension).

It is also important for designers to understand the way that users perceive medical gloves and their effect on performance in order to design gloves that are desirable and give confidence to the user. The interviews conducted with a range of practitioners (Chapter 4) highlighted a number of common perceptions, and a number of these were investigated during the testing. Users felt that nitrile gloves performed worse than latex, particularly that they had poorer fit and elasticity and therefore caused greater loss of tactility. However, tactility testing (Chapter 7) showed little difference between latex and nitrile examination gloves, and the nitrile gloves actually outperformed the latex in the most discriminating test. When asked to rate their performance in each hand condition immediately after testing, no significant differences between the latex and nitrile gloves were found in any of the tests. This suggests either that the specific gloves provided were not representative of latex and nitrile gloves as a whole, that the tests were not reproducing the conditions in which differences are experienced, or that the opinions expressed in the interviews were influenced by factors other than performance. Further investigation of the subjective elements of performance by surveying opinion during real medical tasks would help to determine whether the conflicting results are due to the inadequacy of the tests, or whether differences that do exist are too small to be relevant in the performance of real tasks. Comfort of gloves and the ease of donning were also identified as important issues for users, although these have been studied elsewhere to a greater degree than performance.

13.2. Relevance to glove selection for specific tasks and roles

While the optimum values of some glove properties, such as elasticity, are the same for any task or role – high elasticity produces better conformity to the hand – other properties such as fit, thickness and frictional characteristics produce different effects in different tasks.

Analysis of the effect of fit on performance (Chapter 9) found that loose gloves reduce dexterity performance, while tight gloves reduce tactility. Thinner gloves generally improve performance, particularly in tactility, but reduce tear strength. The choice of fit and thickness will therefore depend on the priorities of the practitioner and the risks involved. This is already seen in the differences in glove selection between microsurgeons and orthopaedic surgeons, but it could be that other specialties could benefit from advice on glove sizing selection or from a larger range of gloves. Those performing primarily dextrous tasks such as suturing will require tighter gloves, while those performing primarily tactile tasks such as examination may require slightly looser gloves.

The tests designed and recommended in this study give designers the tools to answer some of these questions more fully and thus to provide a range of gloves that balances performance requirements with safety and cost considerations.

13.3. Recommendations for future work

Further validation, with a larger sample size, of all the tests recommended will provide greater confidence in the battery of tests as a reliable tool for medical glove evaluation. Some of the tests, such as the Pulse Location Test. also require some modification to enable accurate benchmarking of gloves. Once this has been completed, the tests will provide the opportunity to examine individually the effects of thickness, elasticity, frictional properties and fit on performance across a range of representative tasks.

Although access to clinicians during real medical procedures entails a number of hurdles in terms of both ethics and availability, it would be beneficial to validate the results of the tests, where possible, with real measures of short- and long-term performance.

For cost and availability reasons, the current study was concerned primarily with examination gloves, but the same methods can be used for surgical gloves, which are designed for use in situations where dexterity and tactility are much more critical. Surgeons are currently resisting the introduction of non-latex surgical gloves except for cases of known latex allergy. Studying the performance of a larger sample of surgeons in the tests recommended in Chapter 12, with a range of latex and non-latex surgical gloves, will give a much better idea of whether concerns over differences in performance are valid, or whether latex gloves can safely be phased out altogether.

It is also recommended that further research is carried out to understand the frictional properties of gloves, particularly when lubricated. Differences in performance between gloves were noted by some practitioners to be more apparent in lubricated conditions. A number of the dexterity and grip tests could be repeated in lubricated conditions, if surgical conditions can be realistically simulated through appropriate contaminants (such as fat, saliva and blood). The hydrophilic properties of the gloves (i.e. the ability of the surface to be wetted) could also be investigated using a goniometer. This might yield an explanation of perceived differences in the wet.

Further investigation of the way the glove interacts with the hand would also be beneficial. While some tentative conclusions have been drawn about the effect of fit on tactility and dexterity, the reasons for the observed behaviour are not well understood. Analysis of the distribution of strain in the gloves when worn, through techniques such as Digital Image Correlation [185], and investigation of the movement of loose material on the hand during manual tasks, could help to understand the key issues and suggest possible design solutions.

It is hoped that the tests designed and the data gathered in this study can eventually lead to a more scientific process of medical glove design in which performance, as well as barrier integrity, is a significant consideration, and through which better, more appropriate gloves can be designed and procured in order to improve patient and practitioner safety.

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Appendix A – Test Rig Apparatus

Figure A 1. Jamar® Hydraulic Hand Dynamometer (reproduced from [186])

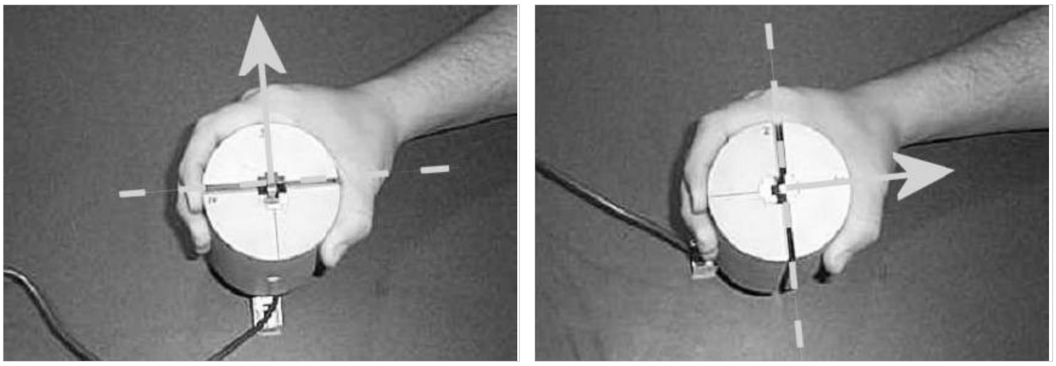


Figure A 2. Split cylinder dynamometer (reproduced from [108])

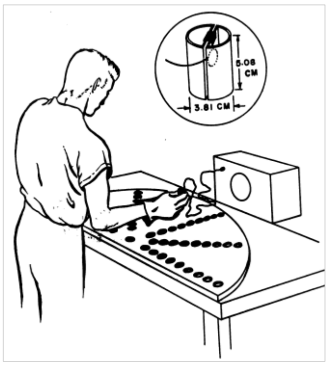


Figure A 3. Cylinder and holed board experiment (reproduced from [58])

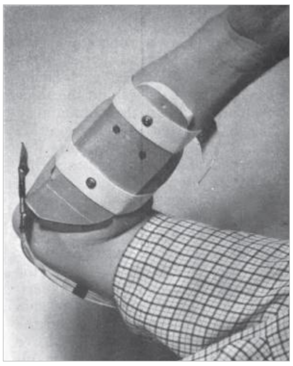


Figure A 4. Muscle force transducer (reproduced from [58])

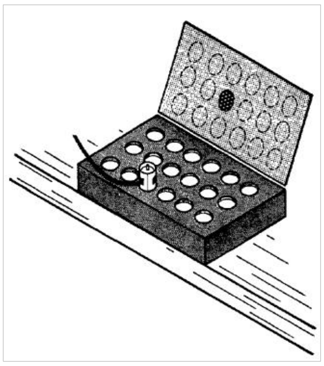


Figure A 5. Cylinder and light bank manipulation test (reproduced from [109])

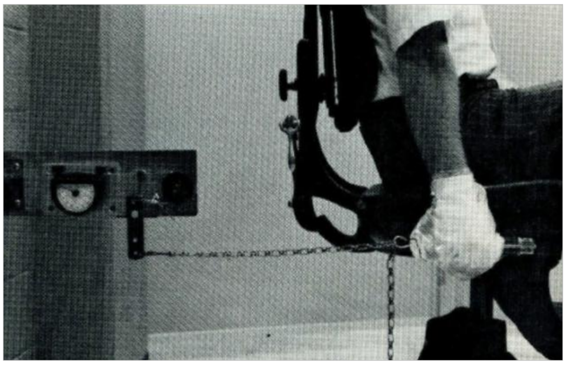


Figure A 6. Forward handle pull (reproduced from [112])

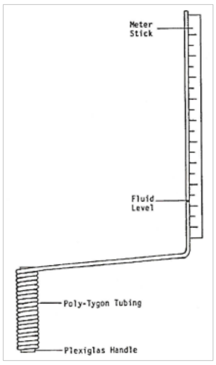


Figure A 7. Tubing wrapped handle (reproduced from [45])

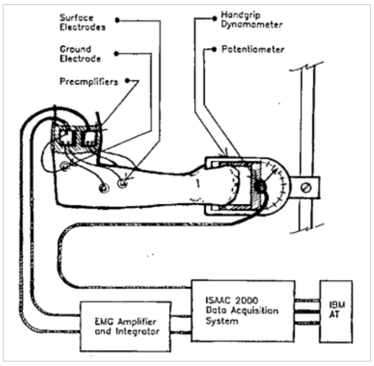


Figure A 8. Hand dynamometer with EMG (reproduced from [49])

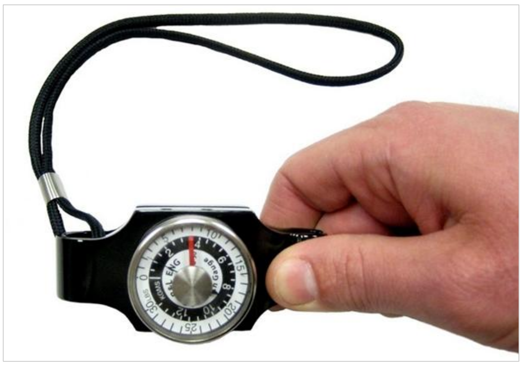


Figure A 9. B&L Pinch Gauge (reproduced from [187])

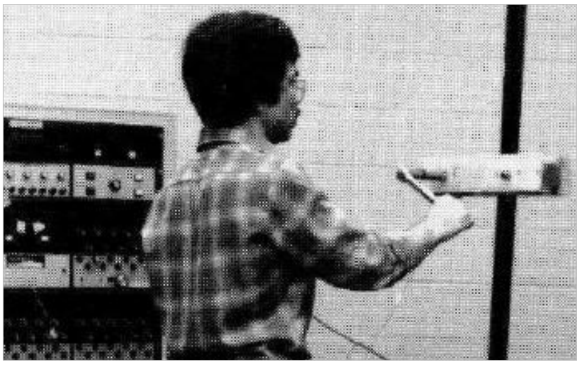


Figure A 10. Wrench torque with EMG (reproduced from [50])

Table A 1. The 20 subtests in the Sollerman hand function test (from [116])

1. Put key into Yale lock, turn 90
2. Pick coins up from flat surface, put into purses mounted on the wall
3. Open/close zip
4. Pick up coins from purses
5. Lift wooden cubes over edge 5 cm in height
6. Lift iron over edge 5 cm in height
7. Turn screw with screwdriver
8. Pick up nuts
9. Unscrew lid of jars
10. Do up buttons
11. Cut play-doh with knife and fork
12. Put on Tubigrip stocking on the other hand
13. Write with pen
14. Fold paper, put into envelope
15. Put paper-clip on envelope
16. Lift telephone receiver, put to ear
17. Turn door-handle 30
18. Pour water from Pure-pak
19. Pour water from jug
20. Pour water from cup

Score:

4	The task is completed without any difficulties within 20 sec and with the prescribed hand-grip of normal quality.
3	The task is completed, but with slight difficulty, or the task is not completed within 20 sec, but within 40 sec, or the task is completed with the prescribed hand-grip with slight divergence from normal.
2	The task is completed, but with great difficulty, or the task is not completed within 40 sec, but within 60 sec, or the tasks is not performed with the prescribed hand-grip.
1	The task is only partially performed within 60 sec.
0	The task cannot be performed at all.

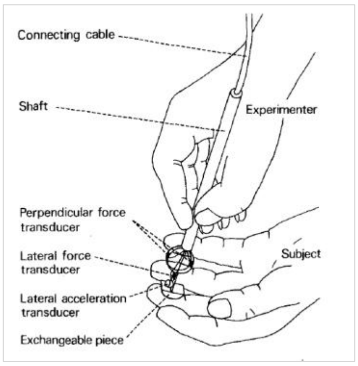


Figure A 11. Force probe (reproduced from [30])

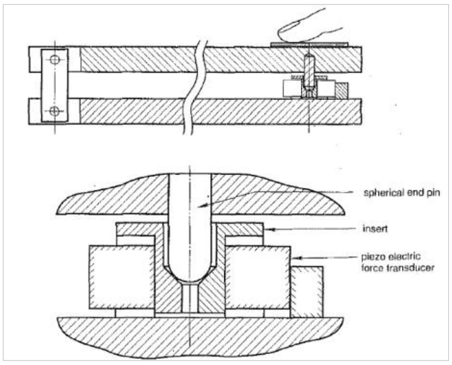


Figure A 12. Keyboard transducer (reproduced from [23])

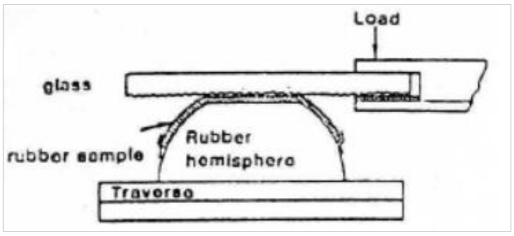


Figure A 13. Rubber hemisphere friction test (reproduced from [119])

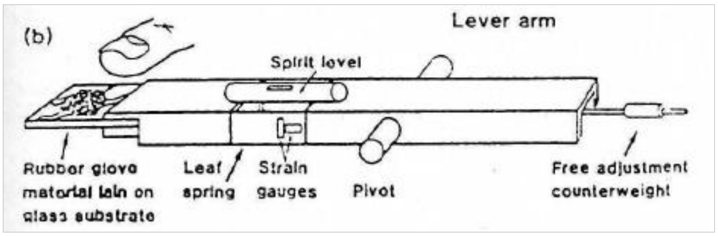


Figure A 14. Balanced pivot finger friction test (reproduced from [119])

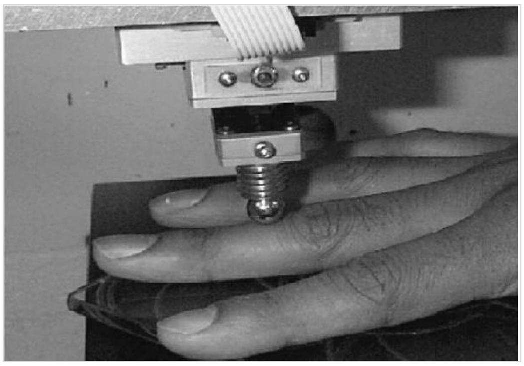


Figure A 15. Universal Micro-Tribometer (reproduced from [120])

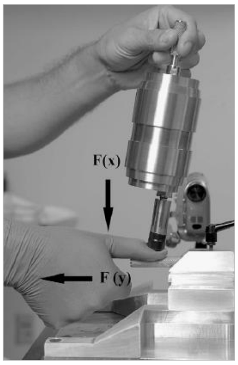


Figure A 16. Dental tool on force plate (reproduced from [26])

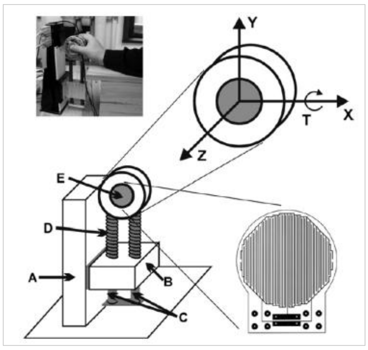


Figure A 17. Linear translation stage

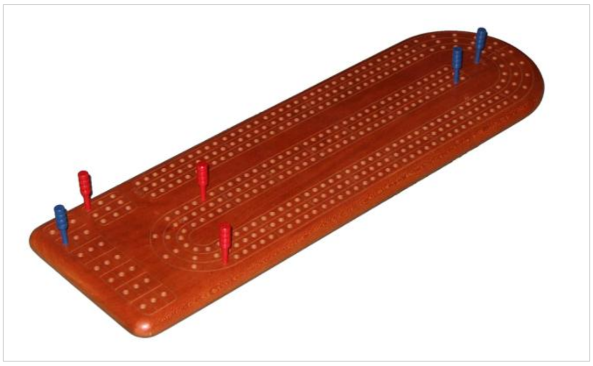


Figure A 18. Cribbage board (reproduced from [188])

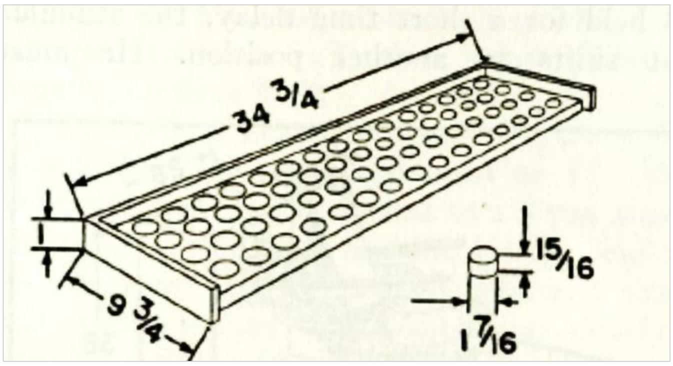


Figure A 19. Minnesota Rate of Manipulation Test (reproduced from [123])

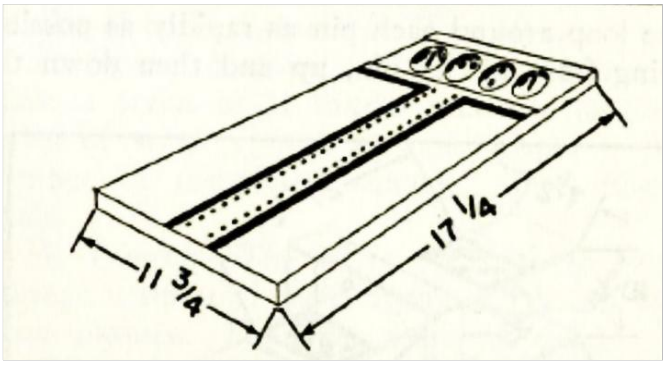


Figure A 20. Purdue Pegboard Test (reproduced from [123])

Figure A 21. Grooved Pegboard (reproduced from [189])

Figure A 22. O'Connor Finger and Tweezer Dexterity Tests (reproduced from [190])

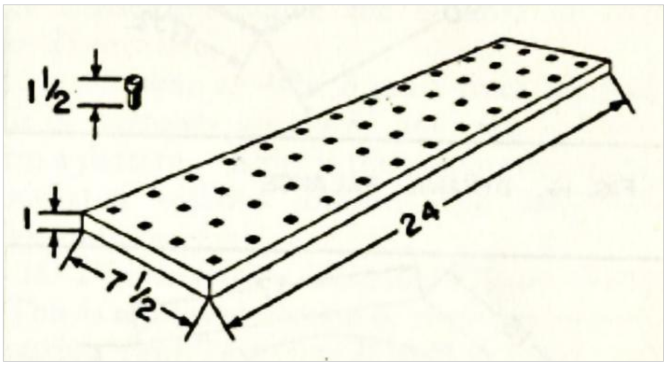


Figure A 23. Santa Ana Finger Dexterity Test (reproduced from [123])

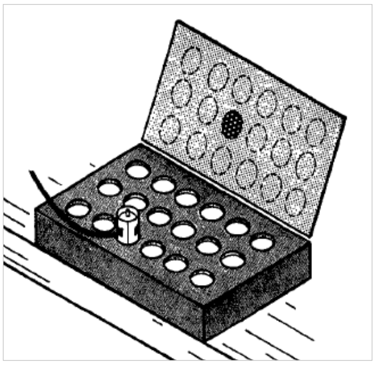


Figure A 24. Cylinder/light bank manipulation test (reproduced from [109])

Figure A 25. Bennett Hand-Tool Dexterity Test (reproduced from [191])

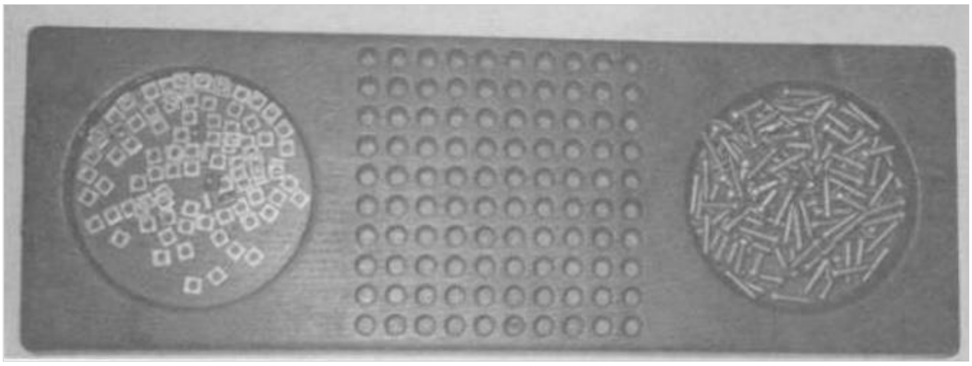


Figure A 26. Pennsylvania Bi-Manual Worksample Assembly Test (reproduced from [192])

Figure A 27. Crawford Small Parts Dexterity Test (reproduced from [193])

Figure A 28. Sponge and Glue Test (reproduced from [53])

Figure A 29. Correx dynamometer (reproduced from [194])

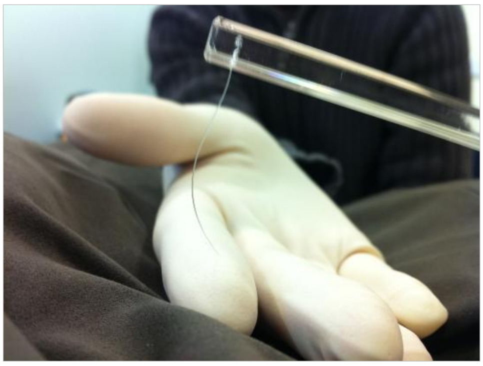


Figure A 30. Semmes-Weinstein Monofilaments

Figure A 31. Touch-Test 2-point discriminator (reproduced from [195])

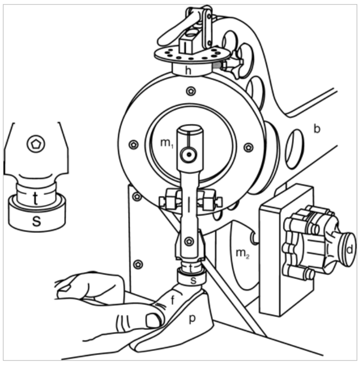


Figure A 32. Computer-controlled stimulator (reproduced from [40])

Figure A 33. Typodont (reproduced from [196])

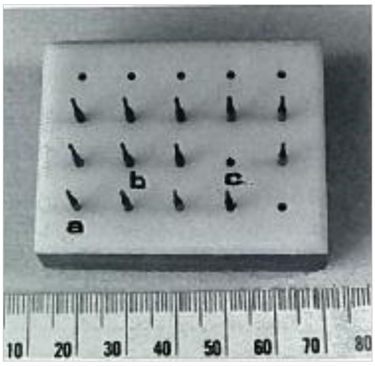


Figure A 34. Bur block (reproduced from [74])

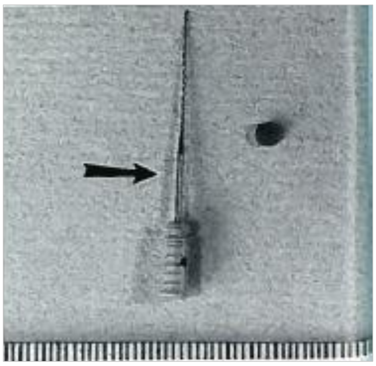


Figure A 35. Endodontic file test (reproduced from [74])

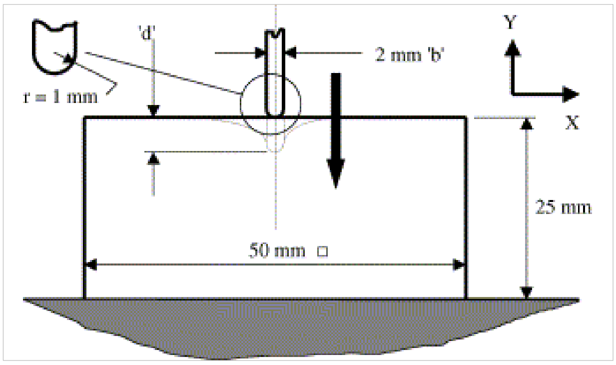


Figure A 36. Plane strain indentor (reproduced from [144])

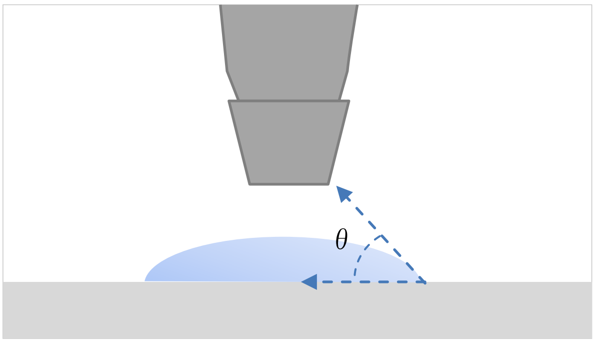


Figure A 37. Contact angle measurement

Appendix B – Ethical Approval Documentation

Medical Glove Interview Guide

Peter Mylon *STH15612 / v.1.0 / 29.01.2010*
Department of Mechanical Engineering
The University of Sheffield

1. What is your position and area of specialisation (if applicable)?
2. How many years have you been practising?
3. Do you use examination gloves (non-sterile, packaged in bulk)?

    a. How regularly?
    b. What type? [natural rubber latex (NRL), nitrile, vinyl, other, brand if known]
    c. Would you use a different type if you had the choice, and allergy was not an issue?
    d. Describe the main activities for which you use the gloves [examination, administering injections etc.].
    e. Which of the following grasp types best correspond to your main activities?

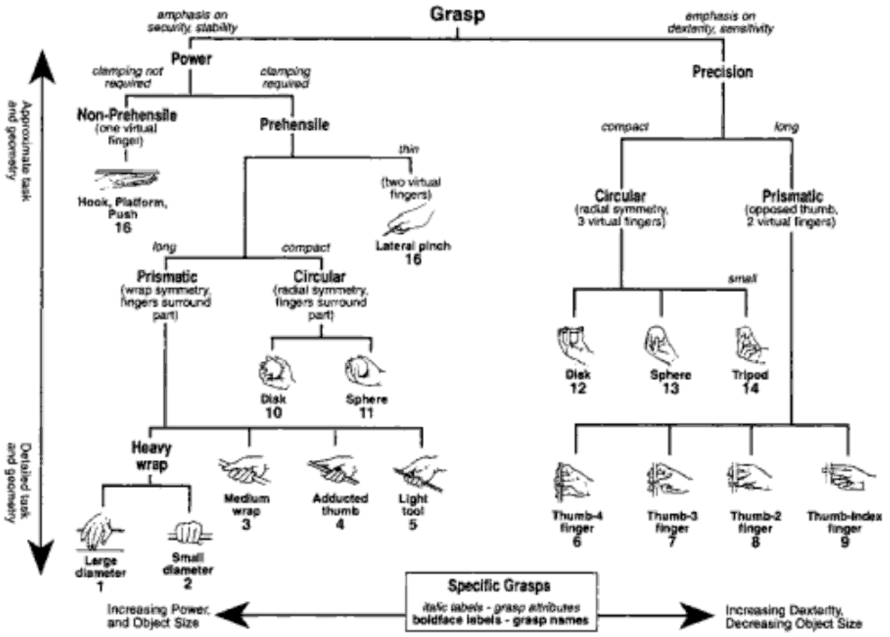


Figure 201 – Classification of Grasp Type – Reproduced from MacKenzie and Iberall (1994), originally from Cutkosky and Howe (1990)

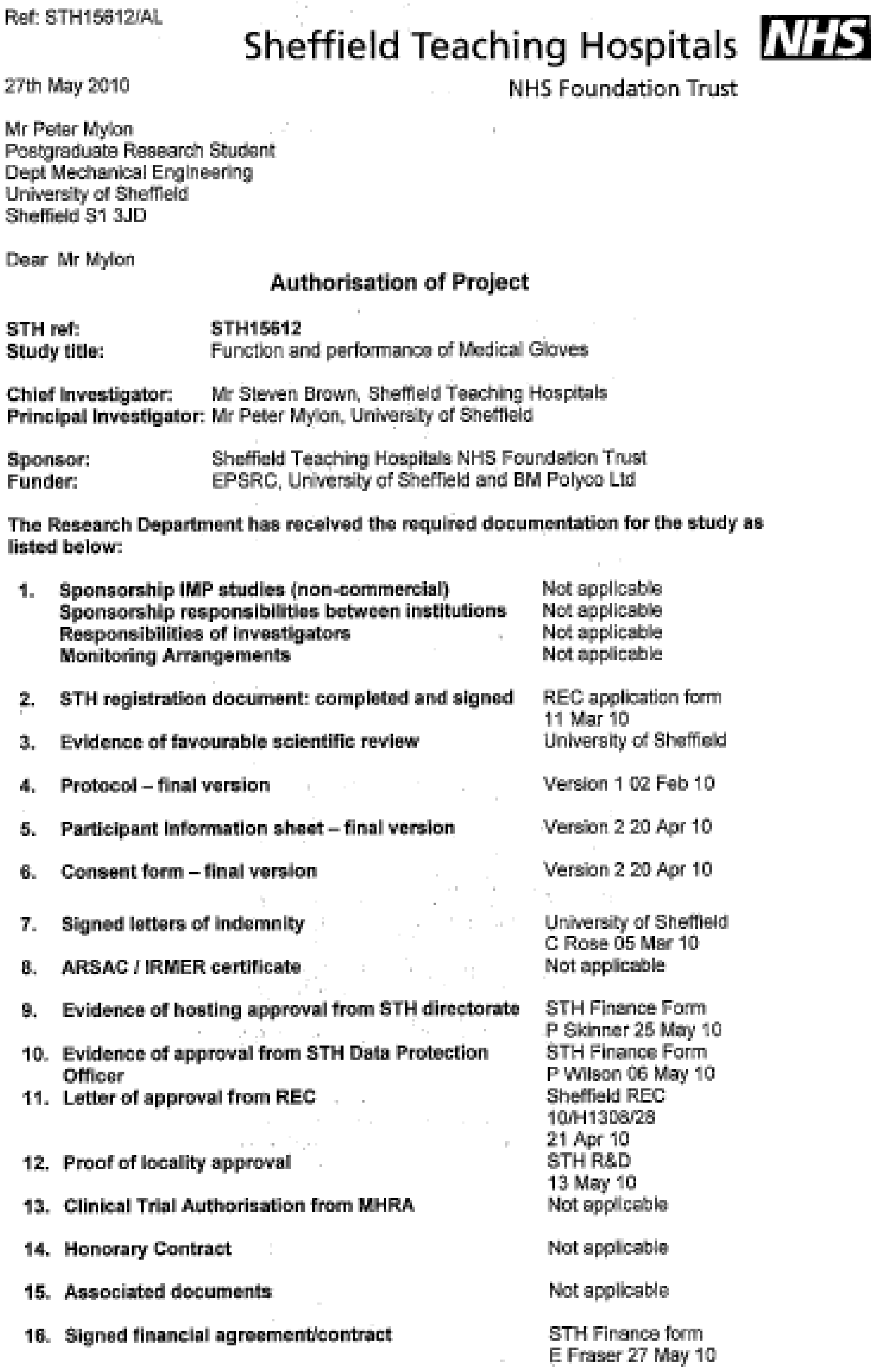
4. Do you use surgical gloves (sterile, packaged in pairs)?

    a. How regularly?
    b. What type? [NRL, neoprene, polyisoprene, brand and type if known]

    c. Would you use a different type if you had the choice, and allergy was not an issue?
    d. Describe the main activities for which you use the gloves [type of surgery etc.].
    e. Which grasp types best correspond to your main activities?

5. For how many years have you been using medical gloves on a regular basis?
6. Which of the tasks that you perform do you consider to require most manual dexterity?
    a. Which grasp types best correspond to these tasks?
7. Which of the tasks that you perform do you consider to require most tactile sensation?
8. After which, if any, of the tasks you perform with gloves do you tend to experience hand fatigue?
    a. Which grasp types best correspond to these tasks?
9. Which of the tasks that you perform do you consider to be most adversely affected by using gloves?
10. During which tasks do you find that gloves are most likely to tear?
11. What do you consider to be the main issue(s) with glove use? [loss of tactile sensation, loss of dexterity, wet grip, dry grip, donning, puncture, tearing, allergy, hand fatigue]
12. What is your perception of how glove performance is affected by the material, thickness, grip pattern, fit or other properties of the glove?
13. Do you take any special precautions with regard to glove use when working in situations where there is a high risk of infection from needle-stick injury?
14. Are there any other issues with medical gloves that you feel need addressing, or useful incidents from your experience with them that might improve understanding in this area?

Confirmation of approval for initial study and amendment



Ref: STH15612/AL

Sheffield Teaching Hospitals NHS
NHS Foundation Trust

27th May 2010

Mr Peter Mylon
Postgraduate Research Student
Dept Mechanical Engineering
University of Sheffield
Sheffield S1 3JD

Dear Mr Mylon

Authorisation of Project

STH ref: **STH15612**
Study title: Function and performance of Medical Gloves

Chief Investigator: Mr Steven Brown, Sheffield Teaching Hospitals
Principal Investigator: Mr Peter Mylon, University of Sheffield

Sponsor: Sheffield Teaching Hospitals NHS Foundation Trust
Funder: EPSRC, University of Sheffield and BM Polyco Ltd

The Research Department has received the required documentation for the study as listed below:

1.	**Sponsorship IMP studies (non-commercial)** **Sponsorship responsibilities between institutions** **Responsibilities of investigators** **Monitoring Arrangements**	Not applicable Not applicable Not applicable Not applicable
2.	**STH registration document: completed and signed**	REC application form 11 Mar 10
3.	**Evidence of favourable scientific review**	University of Sheffield
4.	**Protocol – final version**	Version 1 02 Feb 10
5.	**Participant information sheet – final version**	Version 2 20 Apr 10
6.	**Consent form – final version**	Version 2 20 Apr 10
7.	**Signed letters of indemnity**	University of Sheffield C Rose 05 Mar 10
8.	**ARSAC / IRMER certificate**	Not applicable
9.	**Evidence of hosting approval from STH directorate**	STH Finance Form P Skinner 25 May 10
10.	**Evidence of approval from STH Data Protection Officer**	STH Finance Form P Wilson 06 May 10
11.	**Letter of approval from REC**	Sheffield REC 10/H1308/28 21 Apr 10
12.	**Proof of locality approval**	STH R&D 13 May 10
13.	**Clinical Trial Authorisation from MHRA**	Not applicable
14.	**Honorary Contract**	Not applicable
15.	**Associated documents**	Not applicable
16.	**Signed financial agreement/contract**	STH Finance form E Fraser 27 May 10

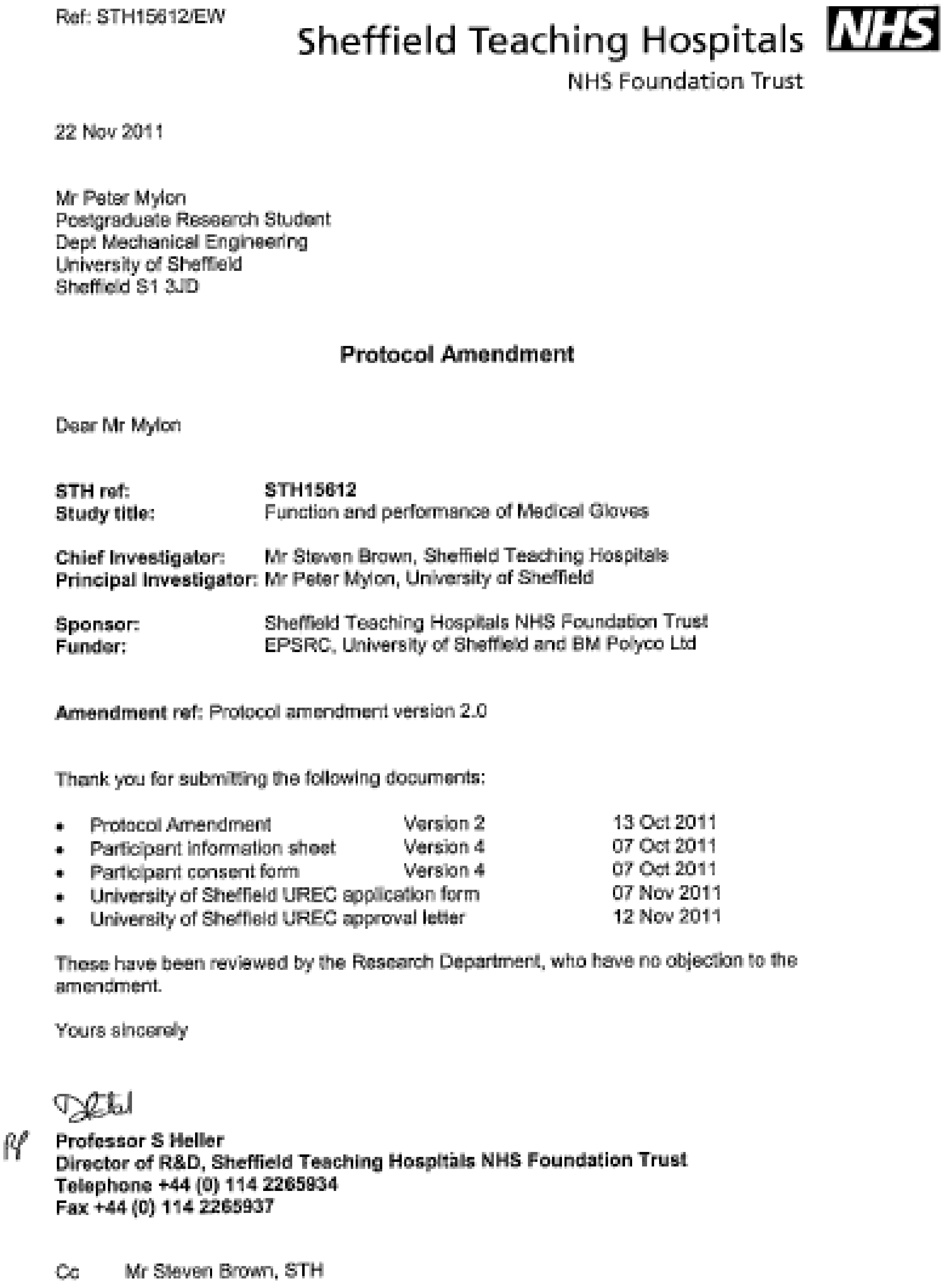
Ref: STH15612/AL

The project has been reviewed by the Research Department and authorised by the Director of R&D on behalf of STH NHS Foundation Trust to begin.

Yours sincerely

pp. Gillie McKay

Professor S Heller
Director of R&D, Sheffield Teaching Hospitals NHS Foundation Trust
Telephone +44 (0) 114 2265934
Fax +44 (0) 114 2265937



Ref: STH15612/EW

Sheffield Teaching Hospitals NHS
NHS Foundation Trust

22 Nov 2011

Mr Peter Mylon
Postgraduate Research Student
Dept Mechanical Engineering
University of Sheffield
Sheffield S1 3JD

Protocol Amendment

Dear Mr Mylon

STH ref: **STH15612**
Study title: Function and performance of Medical Gloves

Chief Investigator: Mr Steven Brown, Sheffield Teaching Hospitals
Principal Investigator: Mr Peter Mylon, University of Sheffield

Sponsor: Sheffield Teaching Hospitals NHS Foundation Trust
Funder: EPSRC, University of Sheffield and BM Polyco Ltd

Amendment ref: Protocol amendment version 2.0

Thank you for submitting the following documents:

• Protocol Amendment	Version 2	13 Oct 2011
• Participant information sheet	Version 4	07 Oct 2011
• Participant consent form	Version 4	07 Oct 2011
• University of Sheffield UREC application form		07 Nov 2011
• University of Sheffield UREC approval letter		12 Nov 2011

These have been reviewed by the Research Department, who have no objection to the amendment.

Yours sincerely

Professor S Heller
Director of R&D, Sheffield Teaching Hospitals NHS Foundation Trust
Telephone +44 (0) 114 2265934
Fax +44 (0) 114 2265937

Cc Mr Steven Brown, STH

Appendix C – Statistical Tests

Tests for statistical significance can generally be separated into two categories: parametric and non-parametric. Parametric tests require variables to have certain parameters – they must be continuous variables that are (approximately) normally distributed across the population. This means that the variable can take any value between its minimum and maximum, and that a histogram of the variable for the sample data approximately fits a normal distribution curve (a bell curve). Some individual tests have further requirements such as equality of variance.

Non-parametric tests do not require these parameters (although some assumptions about the data must still be made). Non-parametric tests are suitable for discrete or non-normally distributed data. While these have the advantage of requiring fewer assumptions and can be used for a broader range of data, parametric tests are preferable as they have more statistical power, i.e. they are more likely to detect statistical differences between treatments. It is therefore necessary to test the validity of the assumptions for a given data set before deciding on the appropriate statistical test.

In this thesis, the Shapiro-Wilk test was used, in which the sample data is compared to the standard normal distribution and the probability that the data came from a normally-distributed population is calculated. If the p value is less than α (0.05 in this analysis), the null hypothesis of normality is rejected.

Where the null hypothesis was not rejected, i.e. the assumption of normality was valid, two tests were used, both of which were “repeated measures” i.e., each subject performed the experiment with every treatment (hand condition):

Repeated-measures ANOVA. Repeated-measures analysis of variance (ANOVA) is used to determine the probability that the means of two or more groups are equal. It compares the systematic variation due to the deliberate changes (e.g., hand condition) with random variation within subjects. If the systematic variation is large compared to random variation, the probability that the means for all treatments are equal will be small, and the within-subjects factor (e.g. hand condition) can be said to have a significant effect. However, this test does not give information about which treatments are significantly different from others.

Paired t-tests. The paired t-test is similar to repeated-measures ANOVA, but only compares two sample groups. It works by calculating the "paired differences" i.e. the difference between scores in the two treatments for each subject. The mean and standard error of the differences are then calculated and the ratio is used to determine the probability (p value) that the mean difference is zero.

Where the assumptions necessary for parametric analysis were found not to be valid, two non-parametric equivalent tests were used. The Friedman test is similar in principle to repeated-measures ANOVA, but instead of using the actual value of the output variable, it ranks the treatments for each subject, and the sum of the ranks for each treatment is compared, giving the probability that the median value is the same for all treatments. The Wilcoxon Signed-Ranks test assesses the probability that the median difference between two paired treatments is zero by calculating the paired differences and ranking them.

Further information on these statistical methods can be found in [197, 198].

Appendix D – Dental Probe Test MATLAB Script

```
% find the max and minimum values in a dataset and compile into a
list

fnames = dir('F:\Data\*.txt')

% put names of all .txt files in directory into an array

dir_length=length(fnames)

% find number of .txt files in directory

av_max=[];

av_min=[];

sdev_max=[];

sdev_min=[];

% create blank arrays for average peak values and standard deviation

for k=1:dir_length

% do the following loop for each file in turn

 file = fnames(k).name

figure

[time,force]=textread(file,'%f %f %*f %*f %*f
%*f','headerlines',23);

% read the first two columns into time and force arrays

f_length=length(force);

% get the length of the force array

[max_loc, max_vals]= peakfinder(force)

[min_loc, min_vals]= peakfinder(force,[],[],-1)

% list values of maxima and minima and location within array

max_sort=sort(max_vals,'descend');

% sort max values into a descending list, i.e highest at top

min_sort=sort(min_vals,'ascend');

% sort min values into an ascending list, i.e lowest at top

v=round(length(max_sort)/5);

% this is the number of max. values selected from the list of peaks
```

```
w=round(length(min_sort)/5);

% this is the number of min. values selected from the list of
troughs

max_list=max_sort(1:v)

% take the top 'v' values from the list, to give the biggest peaks

min_list=min_sort(1:w)


av_max=[av_max mean(max_vals)]

av_min=[av_min mean(min_vals)]

sdev_max=[sdev_max std(max_vals)]

sdev_min=[sdev_min std(min_vals)]

% calculate mean and standard deviation of top maxima and minima

end
```

Appendix E - Examples of Sandpaper Profiles

All of the profiles are shown on approximately the same scale for comparison.

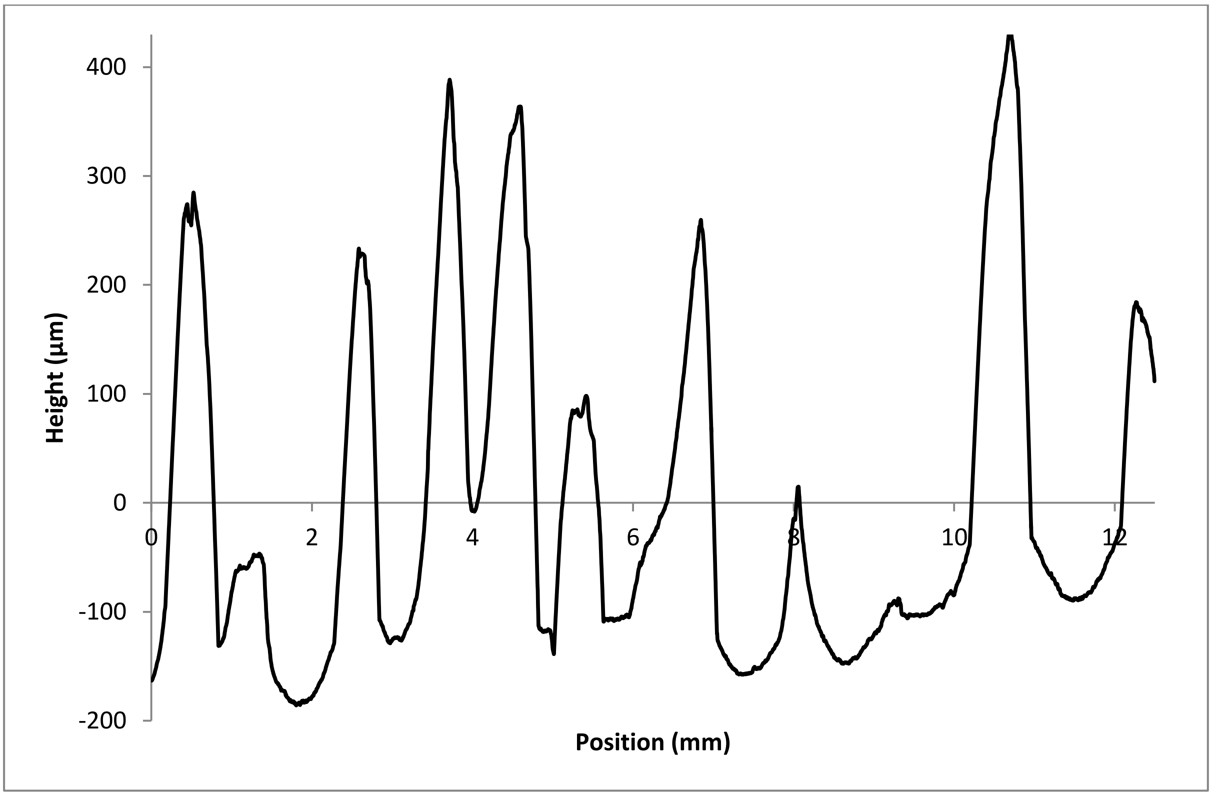


Figure E 1. Example profile of P40-grade sandpaper

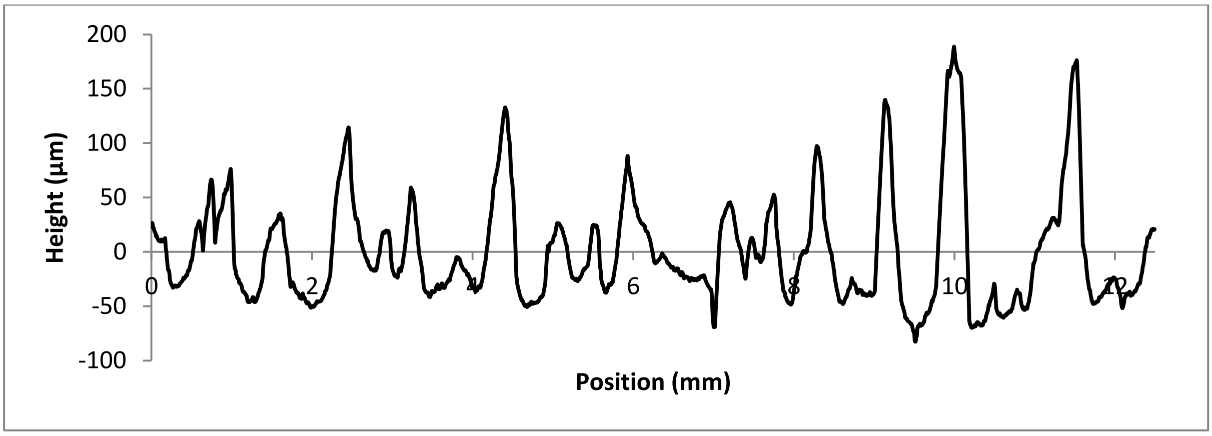


Figure E 2. Example profile of P80-grade sandpaper

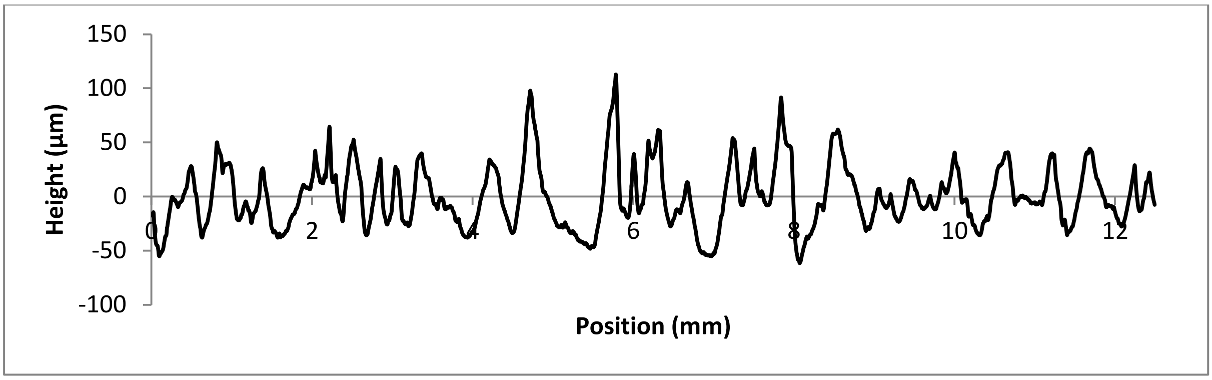


Figure E 3. Example profile of P120-grade sandpaper

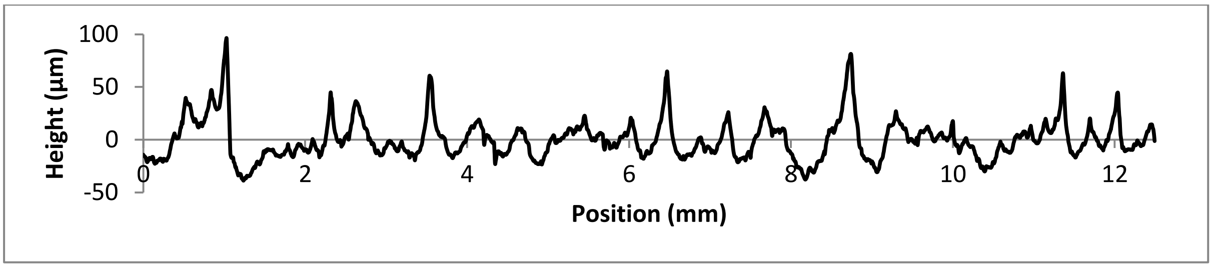


Figure E 4. Example profile of P180-grade sandpaper

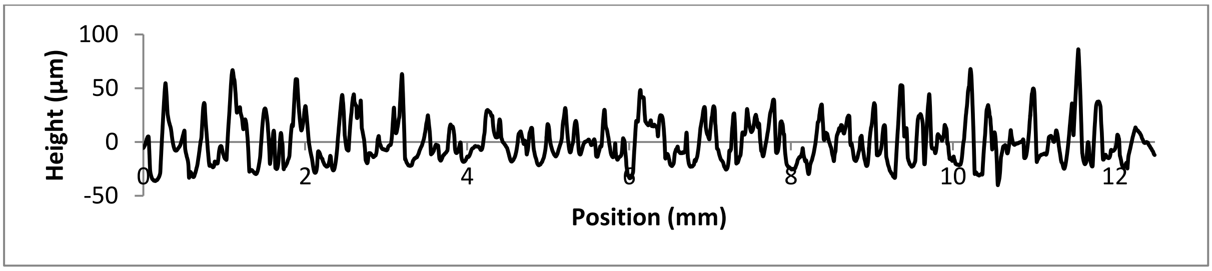


Figure E 5. Example profile of P240-grade sandpaper

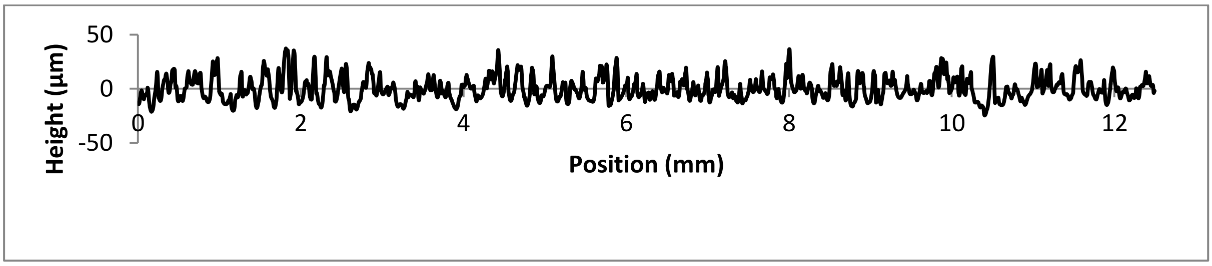


Figure E 6. Example profile of P400-grade sandpaper

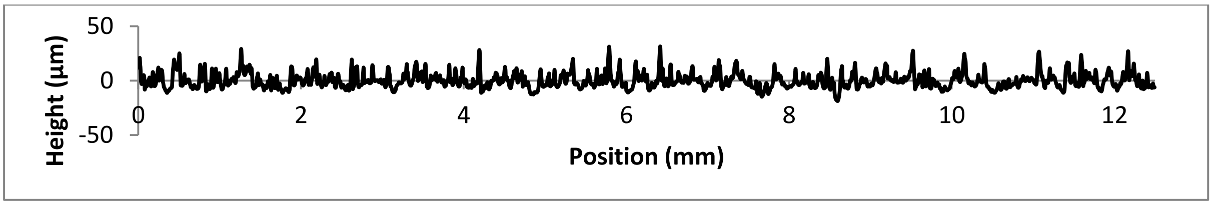


Figure E 7. Example profile of P800-grade sandpaper