The influence of ageing and object properties on prehension

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Inclusion of Work from Solely or Jointly-authored publication(s) in the thesis

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This paper presents a comparison of reach-to-grasp movements of older and younger adults, and how these are affected by object width and texture. Data on older adults' reach-to-grasp movements was gathered by Alexis Lefevre, while data on younger adults' reach-to-grasp movements was gathered by Ian Flatters. Credit for the use of younger adult data as a comparator in Chapter 5 is clearly given to Ian Flatters in the thesis. Mark Mon-Willams processed the data to extract kinematic measures from raw position data: again, this is clearly indicated in the thesis itself. Statistical comparisons between the two groups presented in this paper and in Chapter 5 were carried out by Alexis Lefevre. The text of the paper was written principally by Raymond Holt with input from the other authors, based on Chapter 5 of the thesis.

Abstract

The ability to grasp and manipulate objects is fundamental to many activities of daily living required to maintain independence and quality of life. Physical grip capabilities decline with age; and the functional effect of this can be worsened by environmental barriers. Inclusive design brings a thoughtful approach to the design of products and environments offsetting this decline to ameliorate independent living in later life. As yet, however, little systematic research exists on the effects of object properties on older adults' reach-to-grasp performance. This thesis addresses that gap by exploring the impact of object friction and size on the reach-to-grasp capabilities of older and younger adults, and how these differ.

The research gave an active voice to older adults through focus groups to divulge their difficulties in daily activities that they ascribed to ageing, which provided context to the experimental research. A series of experiments were used to compare the reach-to-grasp behaviour of older and younger adults, and how object size and friction affected this. The research demonstrates that older people adopt slower reach-to-grasp actions in pinch and power grasp, partly due to their lower dexterity. This care, which they acknowledge, is reflected in a more sequential movement, though they exhibit similar grip forces to the younger participants, and participants of all ages scaled their movement and force to object size and friction.

Inclusive design sometimes uses impairment simulators, such as the Cambridge Impairment Simulator Gloves, to help designers understand and empathise with impaired grip capability. Accordingly, the research explored the influence of these gloves on the reach-to-grasp behaviour of young adults relative to that of older users. It was found that by lowering young adults' hand dexterity they forced them to reach-to-grasp performances similar to older adults, allowing the supposition that reduced hand dexterity could partly explain older people's approach.

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I am grateful to all the participants of all ages who willingly came to the University of Leeds, and took part in my experiments with great energy and patience. They respected each protocol with great professionalism while enduring the sound of my French accent, and for that I harbour great respect for them. Jack Graveson's help in running a series of tests with the Cambridge

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Last but not least, much contribution to this thesis was not as tangible as above. Most importantly, I thank my parents for their wholehearted love and support. You have manifested great patience towards me, by keeping on asking me with a smile about my progress even though my answers often sounded more like gibberish to you. I also could not have asked for a better brother and sister who brought me joy from the very first days and took time to visit me in Leeds. Florent, I will never forget that great week-end we spent together before you moved to Belfast, and Elora you will always have my unconditional love.

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Chapter 1

Introduction

"A market is never saturated with a good product, but it is very quickly saturated with a bad one."

Henry Ford

This thesis explores the differences between generations in object handling. Although the ageing population has reached a significant proportion of the global population, and that the growth it experienced over the last few decades is not predicted to slow down, its inclusion in the design process of handheld tools development remains meagre. Keeping the ability to grasp is an important key to maintaining independence and quality of life. Prehension tends to weaken with age, and tools badly suited to these changes can be disabling. Apart from the moral considerations, the actual societal and economical situation of modern societies does not permit the exclusion of the older people from the active population. As the human body and mind evolve throughout the course of life, there is a need to understand the dimensions of the differences between generations in terms of object handling. This research sets out to characterise some of these dimensions, and their influence on the accessibility and practicality of a given product. If people are to remain active and independent at a later age, the workplace and home environments need to be adapted to older people. Although it is evident that comfortable, easy-to-use, and adapted products are favoured by users, these evaluations are too often based on able-bodied users. The growth in size of the ageing population results in a large quantity of users and consumers who possibly have a different definition of what constitutes a comfortable product. Furthermore, products designed to be accessible for those with impaired or reduced prehension often present benefits and greater comfort to those with unimpaired abilities too.

1.1 Background

The research undertaken in this thesis flourished from the conceptual desire to help older people remain independent and retain good quality of life. This section covers the origin of the project, and the research domains and principles on which the thesis is based. This work, part of a large project supported by the White Rose Consortium, studied reach-to-grasp actions and grip force capacities across different ages, because ill-suited handheld tools can generate impairments and affect healthy living.

1.1.1 Designing for Older People

Many minds, knowledge and skills are involved in the creation of a new product or the improvement of an already existing one. Research and development resources aim to create innovative and efficient designs. The work in this thesis investigates a specific category of end-users so as to provide insights on the effects of certain product characteristics on users' handling performances. The expected outcomes of this research work for the improvement of design guidelines is likely to force the development of more inclusive designs.

Inclusive design is the design for an increased product's scope where its accessibility is increased in order to make it useable by the largest population possible. Inclusive design supports better engineering design that aims at improving this design process by improving current knowledge and generating new tools and methods (Clarkson et al., 2007; Keates & Clarkson, 2003). The purpose of a product will guide its development. Engineers and designers want to create the most successful product possible. The best way to do so is by targeting the right users, and knowing the end-users in order to adapt the product and fit it to their needs and desires. Along the line of history, engineers have targeted their products towards the active population, i.e., fully able adults (Cooper, 2007). Today, considering the older population, and developing adequate and more inclusive products is coherent in social and even financial terms for tool designing companies. The lack of knowledge on the needs and desires of people over 60 years old has generated numerous products ill-suited to their demands and abilities (Clarkson et al., 2003).

As people get older, their bodily functions evolve, and past a certain age some tend to deteriorate; grip force and dexterity being two of them (Campbell et al., 1973; Yoxall et al., 2008). Hand force and dexterity play an important role in object handling and subsequently in remaining active, and the research community has studied the evolution with age of grasp (Mathiowetz et al., 1985), tactile perception (Wickremaratchi & Llewelyn, 2006), and object handling capabilities (Hackel et al., 1992). As yet, however, there has been little research on how object properties affect this – for example, how the size or surface of an object might make the object easier or more difficult to grasp as a function of age.

1.1.2 The White Rose Studentship

This thesis compiles research undertaken as part of a White Rose Studentship Network on "Understanding object handling interactions through experiments and simulations." The network brought together researchers at the Universities of York, Sheffield, and Leeds to investigate ways of improving the handling of kitchen tools for the ageing population. Each university represented a different area of expertise and was addressing different aspects of this overarching topic. Sheffield researched how physical characteristics such as strength, skin friction and dexterity change with age, and how these affect object-handling interactions. York investigated the psychology surrounding cooking and the kitchen environment, the experiences and requirements of the older users, and their interactions with the kitchen and the objects it contains. After questioning older people about their struggles in their own kitchen, Leeds dissected the reach-to-grasp, and lifting movements of young and older adults. This thesis focuses solely upon the work done by the author at the University of Leeds.

1.1.3 Object Handling

Object handling is the result of a complex process involving many bodily functions. The most obvious body part involved being the hand; it has been studied in terms of handgrip force and finger force distribution (Freund et al., 2002; Shivers et al., 2002; Westling & Johansson, 1984; Winges & Santello, 2005), skin properties (Comaish & Bottoms, 1971), tactile perception (Barnes et al., 2004; Hollins et al., 1993; Stevens & Choo, 1996; Wu et al., 2004), or muscular synergies (Weiss & Flanders, 2004). The hand is such a complex limb that even after decades of investigations, research is still ongoing today (Enders & Seo, 2011; Flatters et al., 2012; Shao et al., 2010). Some even tried to model the human hand and fingers mathematically or in 3D (Brook et al., 1995; Buchholz & Armstrong, 1992; Yoshida et al., 2006). On top of it, the brain and the whole sensory system also bear a crucial role in handling (Valero-Cuevas, 2005; Westling & Johansson, 1987). Whether it is to know more about the interaction between the nervous system and the hand, or to evaluate one's ability, or even for minimizing the upper extremity injuries within the workplace, object handling covers a tremendous amount of diverse domains such as grip force, movement coordination, or tool design optimisation.

Despite the importance of mastering object handling interactions and the large amount of work done in the area, sparse information on object handling and ageing, and on characterising the physical changes with age exists. All the body parts involved in object handling are affected to a certain extent by age, but individuals are not affected by age in the same way or at the same pace. It is a tedious enterprise to cluster the changes due to ageing and the ones due to pathologies, such as arthritis. When no pathology is reported the term 'healthy ageing' is used in this thesis to characterise the global effects of ageing and the general lowering of abilities. Understanding object handling for older people would result in knowledge that would help designers and engineers in producing products adapted to the ageing population. Subsequently, the global population would benefit from these products, because advanced age globally intensifies difficulties that the active population might encounter. Therefore, making life easier for them is making it easier for the rest of us.

1.2 Aims and Objectives

This thesis investigates the influence of object properties and ageing on prehension. The following analysis represents an attempt to provide information that, once implemented into handheld tools design processes, would generate improvements helping older people in retaining a good quality of life.

In order to run research effectively the kitchen environment was decided to be the scene for this White Rose project. Some of the studies presented in this thesis are therefore illustrated with kitchen utensils. Leeds' work focused on kitchen utensils and older adults, because independent living and good quality of life involve cooking accessibility. Nevertheless, its findings are generalizable to all handheld tools, and improving tools accessibility for older people improves it as well for younger people. Prehension is tackled in two steps in this thesis: firstly its pre-contact phase, i.e., reach-to-grasp, and secondly its contact phase and handling grip forces. Based on previous work, this thesis concentrates first on precision grip because it is straightforward to represent, dissect, and analyse, but then expends in a final stage on power grip. Before trying to systematically map how prehension evolves with age, it is more reasonable to start by exploring whether there are differences between both ends of adults' life span. As a consequence, every study undertaken in this research was run with a young adults cohort and with an older adults cohort. Many product properties are likely to affect people's prehension. Literature has however shown that size and surface friction are probably the two aspects with the most significant repercussion on grip force capacities and movement approach. They therefore are the focus of this research.

Evolving from the overarching White Rose project, based on the background detailed in the previous section, and framed by the few guidelines listed above, this thesis aims to:

Investigate the effects of ageing, and object size and surface friction, on people's reach-to-grasp and grip force.

Before directly tackling this aim, focus groups were organised to form a context and provide the grounding to put this research into a real-world scene setting. Completing the documentation a literature review brings, giving an active voice to the targeted population (i.e., older people) efficiently steered this thesis' studies. Once the perspective of older people on the causes for their difficulties while using utensils to prepare food in their kitchen were collected, the area of academic novelty fulfilling the aim of this research was defined by four research questions:

1. **Does age affect the way individuals adapt their reach-to-grasp movements to changes in object size and friction? (RQ.1)**

2. **Does age affect the way object size and friction limit the maximum force that individuals can apply to a given object? (RQ.2)**

3. **In what ways, if any, do impairment simulation gloves replicate these effects? (RQ.3)**

4. **Do the influence of object size, object friction and age on reach-to-grasp actions with a pinch grip generalise to those using a power grip? (RQ.4)**

These questions are the vertebrae building the central spine of this thesis. The first and second ones cover respectively pinch grip reach-to-grasp actions and grip force capacities for young and older adults leading to the observation of the effects of ageing and object properties on the whole pinch grip handling action. The third question is tackled throughout the whole pinch grip testing, and involves the testing of Cambridge Impairment Simulator Gloves

(CISG). It helps determining the effects of hand and digits dexterity loss, and its role in older people's behaviour. The last research question is an attempt to widen the outcomes of the findings by applying the pinch grip reach-to-grasp study to power grip.

Having highlighted the aim of this research, objectives were developed to guide the experimental structure of the thesis and bring an answer to the research questions. These are as follow:

1. Review the literature to identify current research on ageing, object properties and grip, and to focus the research scope.

2. Interview older people to improve the understanding of their life style and the difficulties they face daily. The information that can be gathered through questioning the ageing population is likely to supplement the information gathered through the literature review, and help in defining the experimental work to perfectly fit real life difficulties.

3. Through the study of different kinematic metrics dictating pinch grip reach-to-grasp actions, observe the effects of object size, surface friction, and distance. Run the latter study with younger and older adults, as well as with younger adults with hand dexterity reduced by CISG. The divergence in reach-to-grasp actions will provide information on the respective effects of ageing and low hand dexterity.

4. Measure the effects of object size and surface friction on the evolution of younger and older adults pinch grip force capacities, together with the effects of CISG. Observe how they relate with the grip force used to cope with an unpredictable perturbation when lifting objects of different sizes and surface frictions.

5. Through the study of different kinematic metrics dictating power grip reach-to-grasp actions, observe the effects of object size, surface friction, and distance for younger and older adults. Compare the behaviour differences between pinch and power grip reach-to-grasp actions.

The thesis' structure was formed to fulfil the aim of the research and its chapter formation was guided by the objectives (Figure 1.1). Through a succession of quantitative and qualitative experiments this thesis demonstrates that older people have witnessed a decrease in their abilities, and with experience and time they chose to adopt more cautious handling behaviour. This caution appears in the present observations of their reach-to-grasp. However this research work observed that they do not exhibit lower grip force. Furthermore they have shown great confidence when presented with familiar task. Ageing therefore brings lower physical capacities but it also brings experience, which can make people more efficient in familiar tasks.

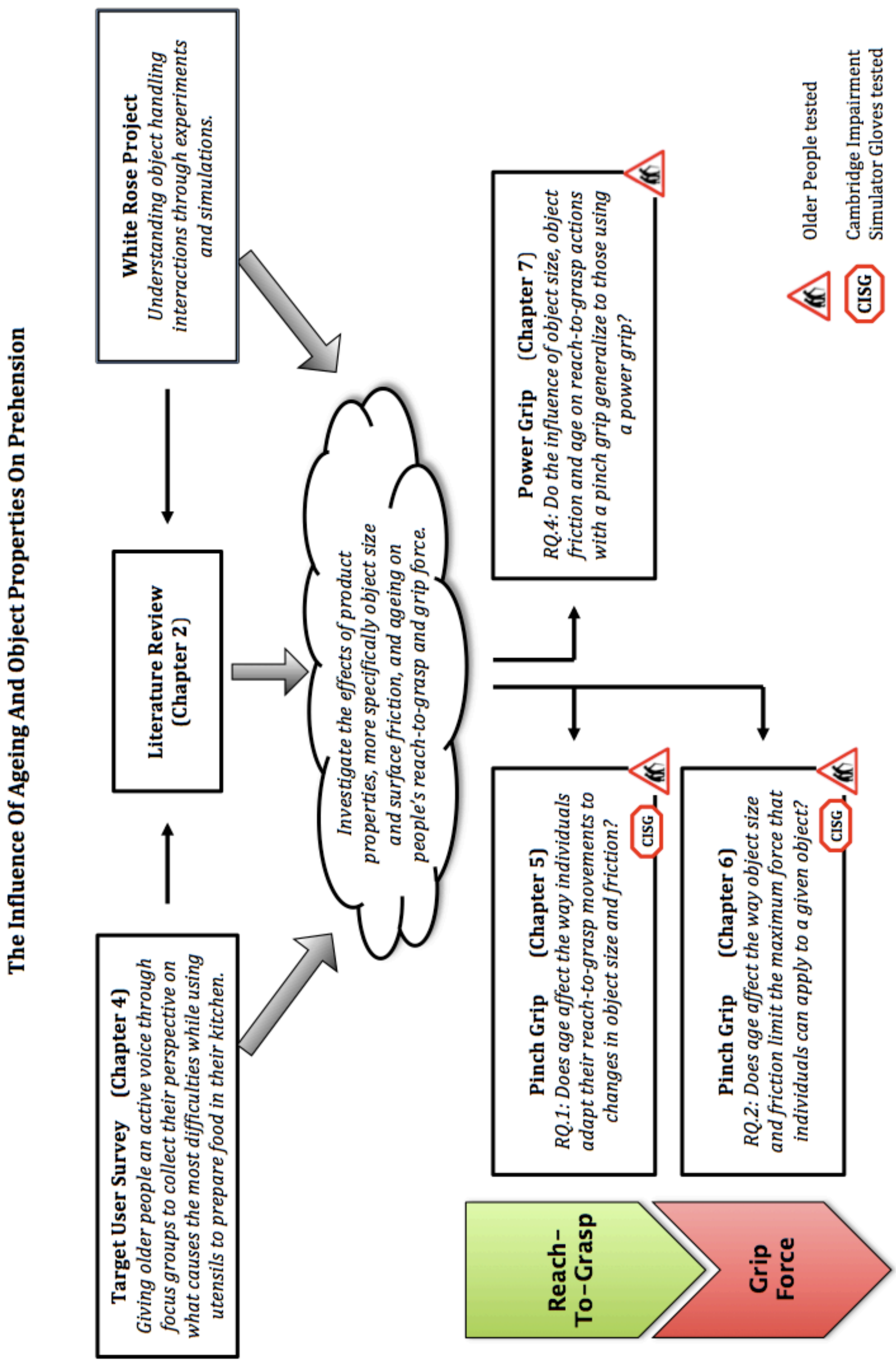


Figure 1.1 An outline of the structure of this thesis showing how the research questions have been addressed in different chapters of this thesis to reach the aim of this research work.

Chapter 2

Literature Review

Developed countries, such as the United Kingdom (UK), observe a growth in size and proportion of their older population. Never in history has there been such a gap between generations. This chapter is a review of the literature used for this thesis' research. Section 2.1 illustrates the growth and importance of the older population, and presents the widening of products' accessibility with inclusive design. In a second section, focus is brought on human hand and grasp depicting the forces in action and the effects of ageing.

2.1 The Ageing Population

2.1.1 Demographic Change

The British population is ageing. Over the last 40 years, improvements in living conditions, health treatments, and hygiene have forced the mortality to drop by 38% and 29% for men and women respectively, leading to the highest life expectancy ever reached in the UK (Dunnell, 2007; ONS, 2011a, 2011b). However, there is a difference between living longer and living a longer healthy life. In 2006 in the UK, men over 65 were expected to live another 17.2 years of which only 12.9 would be considered as healthy living (ONS, 2010b).

Age UK estimated that by 2031, there will be 20 million people aged over the age of 60 in the UK alone (AgeUK, 2013). In addition to that, 85% of new-born babies in developed countries will reach the age of 65 (Kirkwood, 2002). Not only is the number of older people increasing, but also their proportion in the global population: in 1985, 15% of the population was above the age of 65 and 25 years later, 17% is (ONS, 2011a, 2012) The number of the "oldest old" (i.e., 85+) has more than doubled over the same period bringing the median age from 35 to 39.7 (ONS, 2009).

In the UK, the ratio between the active population and the retired population has never been this low in history, and it will keep on decreasing with the coming decades (ONS, 2009). It is projected that in 2035, the 65+ will represent 23% of the population while the 16 and under will only represent 18% (ONS, 2011b), such evolution is predicted for many developed countries (Hagemann & Nicoletti, 1989). All the 27 countries part of the European Union (as of 2012) will see their older people population increases to no less than 19% for Ireland up to 31% for Germany (ONS, 2012). This is the result of the extension of life expectancy and the reduction in birth rate.

On the demographic side of things, this does not appear to be a dramatic issue, yet there is an economical downside as those people come to retire. The active workforce is not large enough to supply pensions for the whole retired population. In the UK, since 2007 there have been more people of state pension age than there are under-16s (ONS, 2011a).

For the economy to thrive people will have to retire at a later point in life; the 60+ must be included in the workforce. Governments are starting to realise that; a realisation reflected by the employment of the 50-64 today (Dunnell, 2007). However, no evolution in employment has been noticed for the 65+. The United Kingdom State Pension Age (SPA) is fixed at 65 for men, and to respect the European Court Ruling women's will be raised to 65 between April 2016 and November 2018, under the Pensions Act 2011. From December 2018 the State Pension age for both men and women will start to increase to reach 66 by October 2020 (DWP, 2011). Both will furthermore be raised to 68 between 2024 and 2046 (ONS, 2010b). At a European scale, SPA is on average at 65 according to the OECD (Organisation for Economic Co-operation and Development) (Hagemann & Nicoletti, 1989). The British government has no choice but to increase SPA, otherwise by 2051, for every person of SPA there will only be two people of working age, while the ratio was of 3.2 in 2008. With the planned SPA changes, it will only fall to 2.9 (ONS, 2010a).

The European Commission suggested that the countries of the European Union should raise their retirement age (EUbusiness, 2010). "*At the moment, there are four working-age people for every person over 65 in the 27-nation EU. That ratio will worsen to two for every person over 65 by 2060*". SPA is being raised in many countries if it has not already been made irrelevant. Governments are changing their national regulations to raise SPA. The ones who did it early stand strong in today's economical crisis. SPA is an important threshold as it can be used to define old age. Indeed, Dunnell explains that old age is "*the age at which a person becomes entitled to receive state pension benefits. Until recently, this tended to be 60 or 65 in most European countries*" (Dunnell, 2007).

2.1.2 There Is Strength in Older People

Being old is not a disease, and does not come with precise symptoms, and yet it is inevitable and concerns everybody. Healthy ageing, representing the normative changes developing with age, as well as the pathologies that tend to spread amongst older people are not specific to one body function or one human characteristic. There is sensory ageing, where sensory systems are deteriorated; this condition provokes for instance the systematic reduction in vision efficiency with age (Sarks, 1976), of which Schieber gives an excellent review (Schieber, 2006). Cognitive functions also suffer a decline (Hanninen et al., 1996), as well as physical abilities (Campbell et al., 1973). Ageing is likely to cause loss of hand strength and dexterity (Yoxall et al., 2008), and reduction of touch sensitivity (Wickremaratchi & Llewelyn, 2006). The difficulties older people have to fight come from those changes that develop themselves into age-related impairments (Grundy & Glaser, 2000). The most notorious of the physical abilities diminution is arthritis: 10 million people in the UK alone are reported to suffer from arthritis making it the most common ageing impairment. The two most common types of arthritis are osteoarthritis (8.5 million people in UK), and rheumatoid arthritis (400,000 people in the UK) (NHS, 2012). Osteoarthritis mostly affects people over 50 but not solely. It is a deterioration of the cartilage in the joints generating rubbing pain at the articulation. Rheumatoid arthritis, more severe, is caused by the attacks of the immune system damaging the joints. They both typically affect the hands, knee, hips, and spine. By inflecting pain, arthritis deteriorates dexterity and muscle strength. People with hand arthritis struggle to get a firm grip, make precise finger movements, or achieve double-actions (such as press and twist for children safe jars). Even reopening one's hand is hard after a prolonged grasp. Nevertheless, arthritis cannot solely be the focus of age related studies since it does not affect the great majority of the older people. Additionally, it is important to note that, while arthritis is much more common in later life, it is not limited to older people and can be diagnosed even in children.

With ageing we, humans, are likely to experience many bodily changes such as less hand sensitivity (Clarkson et al., 2003) provoking a diminution in ability to perceive shapes and textures (Lockhart et al., 2002), but also loss of strength in muscle contraction (Murray et al., 1980), but more importantly a loss in hand strength and dexterity. There are two leading research papers on the effect of age on hand strength: Mathiowetz's and Werle's work (Mathiowetz et al., 1985; Werle et al., 2009). Whilst Mathiowetz has been cited and supported by many (Clarkson et al., 2003; Dennis, 2002; Massy-Westropp et al., 2004; Yoxall & Janson, 2008), Werle's research is more recent and was done with more participants. He found that men's peak grip strength was between 35 and 39 years old, while women's was between 40 and 44, and that pinch strength peaks between 35 and 44 for men and 55-59 for women. He even demonstrated that grip and pinch strength have a curvilinear relationship with age. For Mathiowetz, human beings reach maximum muscle strength between the age of 25 and 35, it then decreases slightly but drastically falls after the age of 50. Even though the results differ between Werle and Mathiowetz, the values presented first a strength increase at a younger age, and then a significant decrease after 50 years.

Such large and crucial studies on the evaluation of handgrip strength follow strict protocols based on the use of specific tools. The tests generally used are the Clinical Assessment Study of the Hand (CAS-HA) (Myers et al., 2007), and the Australian/Canadian Osteoarthritis hand Index (AUSCAN) (Dziedzic et al., 2007). The AUSCAN has become the benchmark, because it is not specific of osteoarthritis. All these strength evaluations consist of a series of tests, which to be reliable have to follow a strict protocol, because hand strength depends on many factors such as arm and body position (Innes, 1999; Kuzala & Vargo, 1992; Massy-Westropp et al., 2004). In addition to that, the same measuring tools are used to ensure tenability between studies, of which the most commonly used one is an analogue hydraulic dynamometer (Jamar) (California Department of Corrections and Rehabilitation, 2010; Mathiowetz et al., 1984; Swanson et al., 1970; Wells & Greig, 2001). This equipment allow the measurement of people's hand strength or hand pain, an estimate of 12 to 21% of the whole population suffers from hand pain (Myers et al., 2007). Nevertheless, these evaluations are limited by the number of participants and their honesty; hand strength can be faked, people can be faking hand weakness (Tredgett & Davis, 2000; Westbrook et al., 2002). Hand impairment does not necessarily mean hand pain, or decreasing hand strength. It also comes in the form of lower dexterity, or restricted active range of motion (AROM), which are evaluated with tests such as the Jebsen-Taylor or the TEMPA test (Bland et al., 2008; Desrosiers et al., 1995b; Hackel et al., 1992; Nedelec et al., 2011). Those researches explain how older people tend to be slower, and that execution time is gender dependent (i.e., Men are faster than women when grip force is needed, while women are faster when dexterity and sensibility is required).

Despite all the existing tools and protocols and the unprecedented growth of the proportion of older people in the population, normative data on older people is sparse compared to fully able bodies. A highly ranked rehabilitation paper: 'Physical therapy' observed that their first publication on geriatric appeared in the 1950s and emphasis only developed in the 80s (Wong, 1988). The amount of research on older people remains shockingly low compared to the proportion of patients over 65 years old in physical therapy treatments. Mathiowetz constructed grip and pinch strength normative data for adults in 1985, but it is only in 1995 that Desrosiers ran a study to build referential data for the aged men as well as women population (Desrosiers et al., 1995a). It is delicate to define a health state by one's age. However, since the abilities of oneself generally diminish sharply after the age of 50, and manual ability is thought to be the best marker of dependency in older people (Jette et al., 1990; Williams et al., 1982), adaptations have to be made if the 65+ are to remain active and independent. To help people to work for longer and live longer healthy lives, their environment is to be adapted to their capabilities. As for technology, people should not have to adapt to the product, but the product has to be adapted to people.

2.1.3 Inclusive Design

Whether it is an infrastructure, a work environment or a simple home tool, the people designing it are not necessarily an exact sample of the people using it. Product designers tend to create products suitable for themselves (Cooper, 2007), meaning an 'able-bodied person', as opposed to an older person who might have some impairments. It is a hard task to put oneself in the position older people are in (Cooper, 1999; Hardigree, 2008). Furthermore, designers do not have the same background as users, and also have different concerns, views, and interpretation concerning design and product forms (Hsu et al., 2000).

A design increasing a product's scope by increasing the product's accessibility in order to make it usable by the largest population possible is called: "inclusive design" (or universal design) (Clarkson et al., 2007; Keates & Clarkson, 2003). It aims at avoiding thoughtless designs of product or environment that turn impairments into disabilities, and by designing for the less-able comfort can be brought to the able population at the same time (Clarkson et al., 2003). Impairment is a condition due to an illness, injury or congenital infirmity. As defined by the Equality Unit of Sheffield City Council: "*A disabled person is a person with an impairment who experiences disability*" (Northern Officers Group, 2003). Disability is therefore not caused by impairment but rather by the social and environmental barriers restricting or removing social interaction. As seen in Section 2.1.2, age is likely to generate impairments, which will affect people's everyday life if their environment is not adapted. Age related impairments thus become disabilities, which can lead to dependency. Poor environment design should not be the cause for loss of independent living. Humanly and economically speaking tools must be suitable for older people. Why develop a product only suitable for young adults when more than 50% of the wealth is owned by people over 50, in the UK (Banks et al., 1994)?

Interest in the functional capacities of older people is growing as seen in Section 2.1.2, and the inclusion of older people in design process and task analysis, such as handling efficiency or navigation through a telephone voice menu is increasing as well. (Clarkson et al., 2003; Grundy & Glaser, 2000; Imrhan, 1994; Sharit et al., 2004). This leads designers to come up with ideas to recreate the older user's experience, such as impairment simulators. When it comes to designing for people whose capabilities do not fit the norms typically assumed by designers (such as older people), a range of different techniques and tools have been developed and added to the researchers' toolbox. Some of those tools, referred to as impairment simulators, are designed to handicap an able body and mimic the effects of one or more disabilities. These simulators are being used more and more often in academia (e.g., Cambridge University's impairment simulators) (Goodman-Deane et al., 2008), or industry (Hardigree, 2008; Steinfeld & Steinfeld, 2001). These tools simulate seniors' physical limitations; hence the designer has a better understanding of the issues encountered by aged people, because it limits one's body abilities typically affected by ageing. Cambridge designed their own impairment simulator gloves, which are meant to reduce people's hand dexterity, and therefore possibly replicate to some extend the difficulties an older person might have or the effect of arthritis (Figure 2.1). Plastic rods strapped along every digit hinder the flexion at each phalangeal joint. Parts of this thesis investigate whether these gloves, referred to as Cambridge Impairment Simulator Gloves (CISG), can force a young and healthy person into behaving like and older person.

Figure 2.1 Cambridge Impairment Simulator Gloves (CISG) designed by the University of Cambridge (Cambridge, 2013).

Unsuitability is found in work and home environments. This thesis research has been applied to handheld tools, more specifically kitchen utensils, because the author believes that here lies an important issue. Whether it is for Activities Daily Living (ADL), addressing basic self-care activities, or for Instrumental Activities Daily Living (IADL), addressing more complex community and household living tasks, food preparation and eating are present in a large amount of scales (if not all) (Bucks et al., 1996; Law & Letts, 1989; Lawton & Brody, 1969). When one looses the ability to cook or feed on its own is when independency is lost. Food access is a primary need, and a human right (United Nations, 1976). Yet because of the weaknesses age brings, some people do not have access to what they like, want or even need in terms of nutrition. The ability to survive, stay independent and retain good quality of life is the result of the interaction between people's capabilities and object properties.

Inclusive design is all about trade-off between accessibility, usability, functionality, and aesthetics. It is also about understanding design exclusion by knowing who is excluded and how the actual design (if there is any) can be improved to diminish exclusion. Inclusive design aims at reducing or eliminating the need for adaptations. In 1997, Ronald Mace led a group of architects, product engineers, and environmental design researchers to develop the seven principles of Universal Design (Connell et al., 1997). These principles are meant to be guidelines for designers and consumers to evaluate existing designs, and guide the design of environments, products and communications. Mace listed them as follow:

- Principle 1: Equitable Use. The design is useful and marketable to people with diverse abilities.
- Principle 2: Flexibility in use. The design accommodates a wide range of individual preferences and abilities.
- Principle 3: Simple and intuitive use. Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level.
- Principle 4: Perceptible information. The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities.
- Principle 5: Tolerance to error. The design minimizes hazards and the adverse consequences of accidental or unintended actions.
- Principle 6: Low physical effort. The design can be used efficiently and comfortably and with a minimum of fatigue.
- Principle 7: Size and space for approach use. Appropriate size and space is provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility.

Universally accessible design is in practice impossible, inclusive design is about being aware of the implications of each exclusion decision made in the design process. For instance, a better designed handheld tool could reduce product discomfort for the able population (Fellows & Freivalds, 1991), reduce injury risk for the whole population (Lewis & Narayan, 1993), while enabling its use to people with lower ability, but in practice cannot be accessible to the entire human population. There are too many differences between humans and discrepancies between impairments for a universal design to fit and attract everyone.

The best way to minimise design exclusion is to know its targeted user's needs and wants. Focus groups help researchers gather precious information about the users by asking them directly (Bahn et al., 2007; Barnes & Lillford, 2009; Bruseberg & McDonagh-Philip, 2001). Focus groups have been run in the present research to gather people's view and get some insights on the daily life of older people. Knowing the strength, capabilities, and limits of the targeted user, here older people, is predominant in the design process of a product, such as a kitchen utensil in the case of the present research. This documentation drastically helps designers in building a user centred product. If one is to help older people remain independent by providing solutions to their problems, one has to fully grasp the difficulties they encounter on a daily basis. Those difficulties mainly come from the interaction with the product through grasp affected by grip strength losses.

With age, physical and mental ability tend to decline, turning the kitchen into a hostile environment. This hostility comes from different reasons like inoperable packaging, inaccessibility of groceries, inadequate utensils, and many more (Holt & Holt, 2011; Rowson & Yoxall, 2010). In the interest of bringing a solution to this problem, many things can be improved. There are a lot of unexplored research domains in regards to aging that need to be tackled, such as product design and hand grasp. Cooking is a manual task that requires the use of tools, tools that can induce pain and discomfort. Kitchen utensils are not for the most part designed with the older population in mind. They must be improved by being adapted to the widest population. This thesis tries to provide a better understanding of people's grasp and of the differences between two distinct age groups in order to bring important information to designers to help them improve kitchen utensils' design. Because even if aesthetics takes a great part into product design and is easier for users to evaluate, ergonomics must not be forgotten (Helander, 2003).

2.2 Grip and Manipulation

2.2.1 The Human Hand

Generally, humans rely on their senses in the following order: vision, touch, smell, audition and taste. Senses' importance is not sex-related but can be age-related (e.g., older people find smell more important than young) (Fenko et al., 2009; Schifferstein, 2006). We, as human beings, interact with the world around us, and a lot of this interaction goes through our hands, whether it is to pet a cat, weigh a fruit, feel the warmth of a fire, grab and lift an object, or simply write a letter. Hands and touch are used continuously and are primordial in certain situations, as touch is the only way human can perceive temperature (Jones & Berris, 2002; Yang et al., 2006) and weight (Schifferstein, 2006). Tactile perception has been intensively researched (Hollins et al., 1993). Our hands are very sensitive, especially the fingertips, one of the most sensitive human body part. We perform numerous actions using our hands everyday including cooking and eating, which is why hand grasp is at the heart of this research. Hands and touch have been researched for a long time and in many diverse domains. The hand has been dissected to observe its muscle, bones, joints, and skin (Jones & Lederman, 2006; Weiss & Flanders, 2004). The hand is constituted of 27 bones and 29 muscles, which are innervated with the skin of the hand. The skin consists of two distinct layers, the epidermis providing a protection barrier, and the dermis containing the nerve endings critical for grasp (Jones & Lederman, 2006; MacKenzie & Iberall, 1994). The drawing of the hand by the American Society for Surgery of the Hand (ASSH) reported in Figure 2.2 lists hand parts to which reference can be found in this thesis.

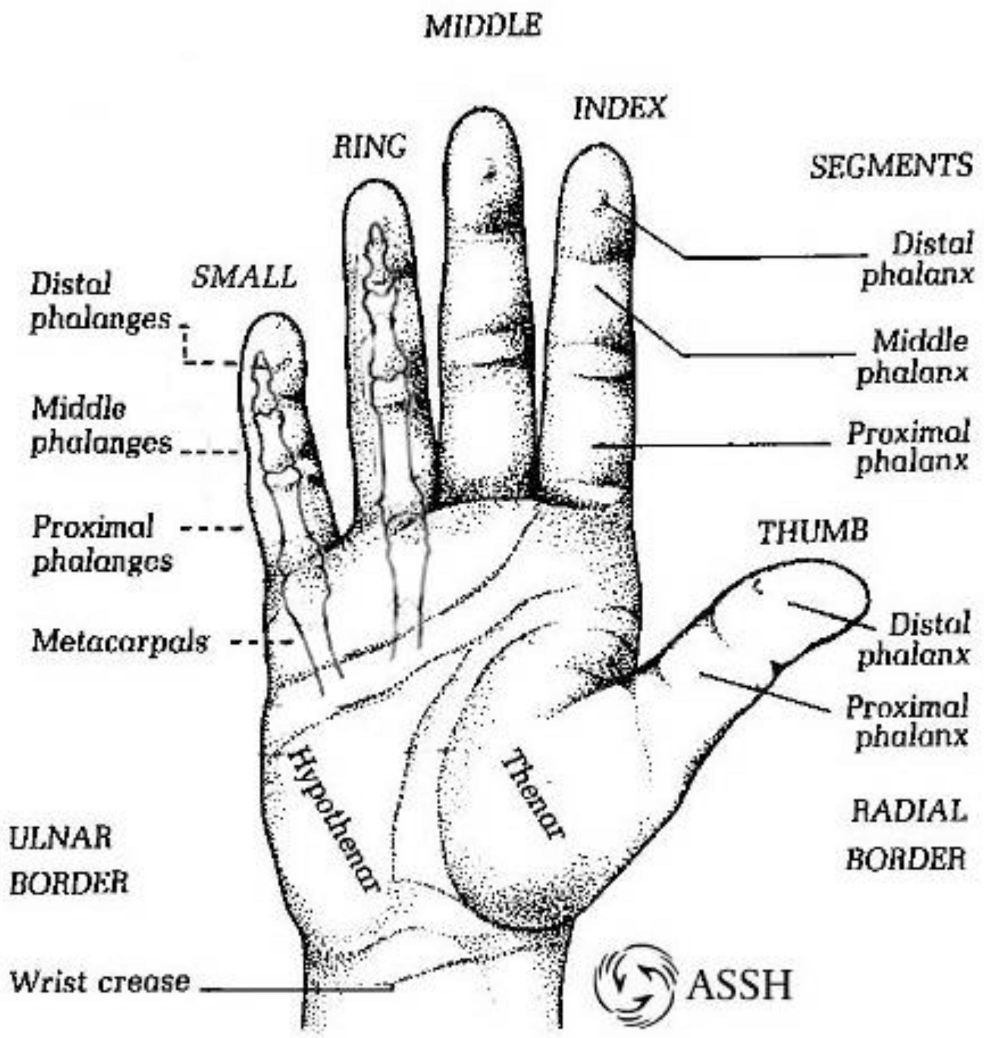


Figure 2.2 Sketch of a human hand retrieved from the American Society for Surgery of the Hand (ASSH) (ASSH, 2009).

Hand skin is divided in layers containing mechanoreceptors (receptors detecting shape, vibrations, temperature, movement, pressure); they are what make hand skin so complex and powerful at the same time. They allow the detection of roughness by measuring surface spatial pattern of skin deformation, compliance, slipperiness by measuring the friction between the skin and object surface with the ratio between normal and tangential forces, and thermal conductivity with the speed at which heat is conducted out of the skin (Barnes et al., 2004; Comaish & Bottoms, 1971; Wu et al., 2004). All the information gathered by those mechanoreceptors (Figure 2.3), labelled as touch perception, is transferred to the Central Nervous System (CNS) that processes it and reacts to it. Thanks to technological innovations, researchers have at their disposal tools such as CAD models, finite elements analysis, 2D and 3D artificial finger models (Shao et al., 2010; Yoshida et al., 2006) to shed some light on the hand's complex functioning.

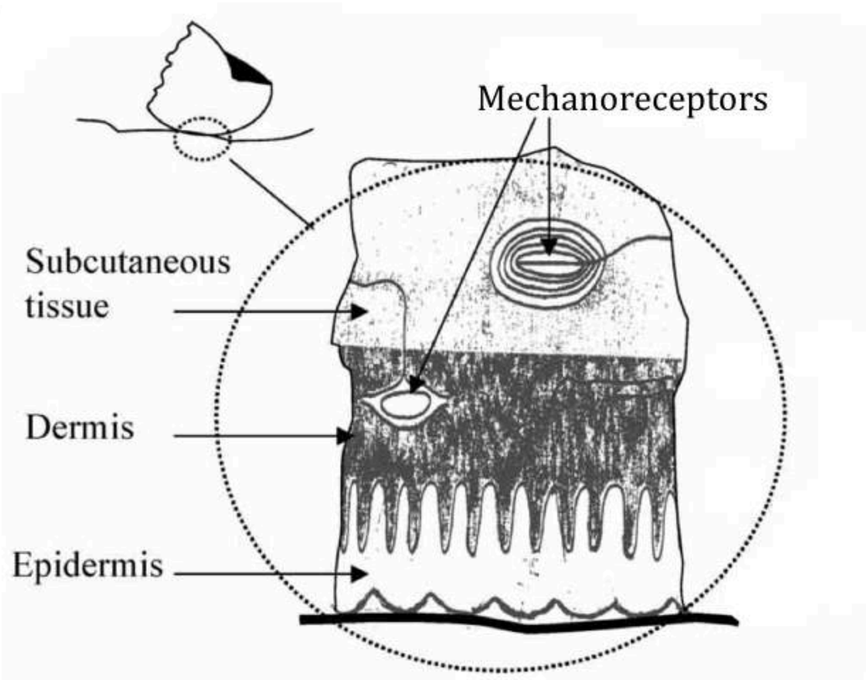


Figure 2.3 Fingertip in contact with a surface stimulating its mechanoreceptors (Childs & Henson, 2007).

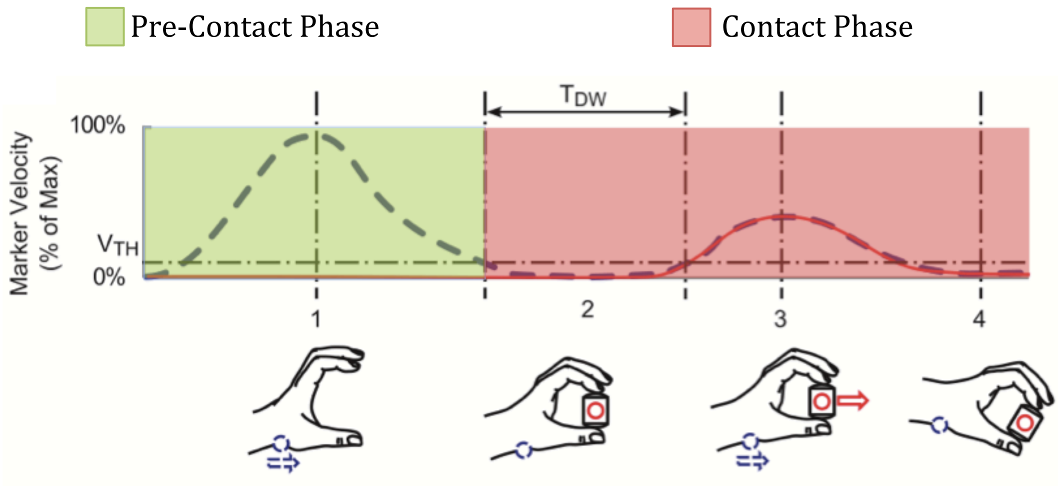
Additionally to the loss of strength with age, hands are, with feet, the limb most affected by cutaneous sensitivity decrease (Stevens & Choo, 1996), making the person apply more force.

2.2.2 Computation of Feedforward and Cutaneous feedback by the CNS

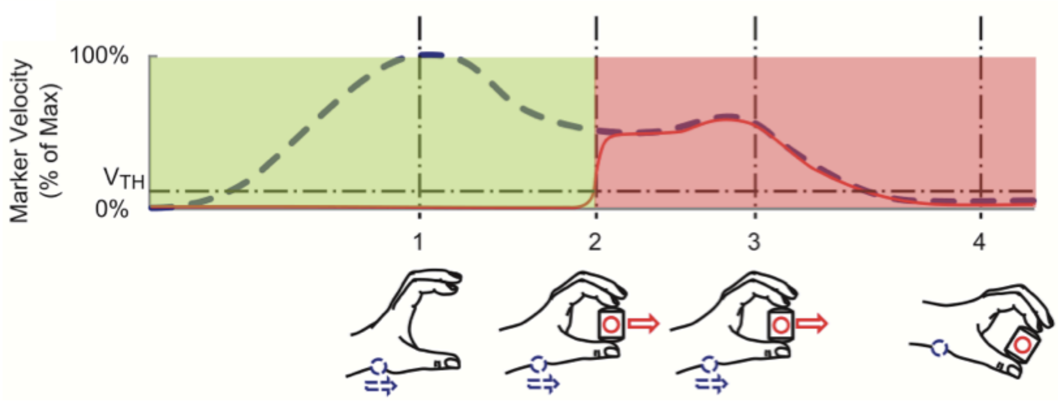
The human body and mind are extremely sophisticated systems, working seamlessly together in an even more complex process. Object handling might appear at first sight as a simple action to most lay people, yet we do not yet have a complete understanding of it. A multitude of organs work seamlessly together with the brain, managing all the information in a complex manner, so that the user can safely and accurately pick up a great variety of objects (Castiello, 2005).

Firstly, hands are a complex mechanical apparatus, solely based on the biomechanical aspect of a grip, many muscles, bones, joints, and tendons have to work jointly to balance the object and apply the required force (Brook et al., 1995; Buchholz & Armstrong, 1992; Fearing, 1986; Jones & Lederman, 2006). The human hand is an impressive, extremely complex, and sophisticated tool (Jones & Lederman, 2006; MacKenzie & Iberall, 1994). Impressive, as it allows many different forms of grip; complex, as many different factors influence its grip abilities, starting with the wrist, and sophisticated since it can adapt itself to many diverse environments; see Winges and Santello for review (Winges & Santello, 2005). Many agree that grip force is highly influenced by wrist torque, and angle (Hallbeck, 1994; Hallbeck & McMullin, 1993; Imrhan, 1991; Morse et al., 2005). Wrist torque and grip force follow an inverted U shape function with wrist angle, peaking at the neutral position (Jung & Hallbeck, 2001), and increasing again at the extremes. This is due to muscle length and tension. Others try to relate hand anthropometry to its performance (Dempsey & Ayoub, 1996; Eksioglu, 2004). Researchers go at length to always know more about object reaching, and hand grasp and strength, and for that they develop new force transducers, new dynamometers, and new measuring techniques (Kutz et al., 2007; Wimer et al., 2009).

Secondly, during that whole process, which starts long before the skin gets in contact with the object, our mind has to process a large amount of reflex and voluntary inputs in a very short period of time, and retransmit the processed data to the limbs. The brain starts sketching the action as soon as the eyes supply it with the first object analysis and properties estimation (Cuijpers et al., 2004; Paulignan et al., 1991). The actor has to reach for the object, place their hands or digits on it, and then secure a grip. Even before fingers are laid on the object, the brain, using sensory cues of different modalities (Ameli et al., 2008), has already gathered information on many factors such as the object's size, and textures (Mon-Williams & Bingham, 2011), or made estimations on the object's properties such as its weight. The CNS controls the movement before contact, or "getting to grasp" as MacKenzie refers to it (MacKenzie & Iberall, 1994), and plans the trajectory, the grasp strategy and hand orientation and location based on the task requirements and object properties. Fingers must be placed to keep the object balanced, as it will be lifted up, and apply the appropriate fingertip forces in order to handle it. This entire reach-to-grasp-and-lift process consists of two phases: first, the pre-contact phase, where the hand is moving towards the object; then, the contact phase, where the skin is in contact with the object (Figure 2.4). The pre-contact phase (or reach-to-grasp) comprises the beginning of the movement when the hand starts moving until it reaches the object.



(a)



(b)

Figure 2.4 Kinematic profiles for (a) 'stop-and-go' and (b) 'fly-through' prehension movements. 1, the hand is in the transport phase with the wrist Infrared Emitting Diode (IRED) reaching peak velocity. 2, the digits contact the object (the approach phase ends, and the contact phase begins); for a 'stop-and-go' movement the hand velocity drops below the threshold velocity (V_{TH}) and remains below it for a period (T_{DW}). 3, upon successful application of the grip, both the wrist and object markers move in unison as part of a second distinct movement. 4, movement complete – hand and object velocity tends to zero (Flatters et al., 2012).

Through both stages, the CNS processes a large quantity of information to successfully perform the task at hand. A reach-to-grasp-and-lift movement interlinks sensory and motor mechanisms to plan, execute, and adapt the hand motion and finger forces (MacKenzie & Iberall, 1994). With past experiences, humans' CNS builds itself an internal model to estimate a grasp situation (i.e., forces and movements required to pick up a targeted object). Therefore, prior to any contact the CNS estimates the entire reach-to-grasp-and-lift movement with a feedforward mechanism relying primarily on visual cues and memory (Buckingham et al., 2009; Cole, 2008; Flanagan & Johansson, 2010). The CNS can evaluate the required forces and foresee the necessary reaching approach with stunning precision and accuracy (Edin et al., 1992; Flanagan et al., 2009; Gordon et al., 1991; Gordon et al., 1993; Johansson & Westling, 1984; Johansson, R.S. & Westling, G., 1988; Wolpert & Ghahramani, 2000). Once fingers get in contact with the object's surface, sensory afferent information is processed by the CNS to map out and adjust grip where the object's properties do not match the predicted properties. The skin deformation stimulates thousands of mechanoreceptors present in the glabrous skin. These afferent tactile signals update the CNS on the object's surface, and the handling behaviour to adopt (Johansson & Flanagan, 2009; Johansson & Westling, 1984). With these signals, the CNS refines its internal model for better future predictions, and adapts arm movement speed and grip force economically and precisely to the handled object's properties, such as shape, weight, and surface texture (Cadoret & Smith, 1996; Hermsdorfer et al., 2008; Johansson, 1998; Westling & Johansson, 1984; Witney et al., 2004).

2.2.3 The Pre-Contact Phase of Reach-to-Grasp Pinch Grip

The whole movement done by the hand to reach and pick up an object is referred to as a 'reach-to-grasp-and-lift' movement. As explained earlier, the body and mind are at work before the hand gets in contact with the aimed object. The initial phase where the hand is reaching for an object, hereby called the pre-contact phase, has a tremendous effect on the success of the grasp of the object. If the pre-contact movement is too sudden, or the object width is misjudged (Bootsma et al., 1994) then the object can be knocked over

(Rosenbaum et al., 1999). The location and geometry of the objet dictates respectively the movement time, and the positioning of fingers and thus the trajectory of the grasp, (Cuijpers et al., 2004; Kleinholdermann et al., 2007). The difficulty of the task will also dictate the speed and accuracy of the movement (Fitts, 1954). Part of this thesis focuses on this pre-contact phase, more precisely on the kinematic of that phase. The movement starts with a fast-velocity initial phase and finishes with a low-velocity final phase (Jeannerod, 1984). Jeannerod also observed in his study that fingers first stretch and then close, but also that the onset of closure correlated with the beginning of the low-velocity phase.

The complexity of the human hand makes understanding reaching and grasping a laborious task. As Napier explained, although the hand can adopt many shapes and forms for a great variety of grasps, this variety can be regarded as two different grasp techniques: a precision and a power grasp (Napier, 1956). Small objects are handled between digits in a precision grip where control and precision prevail over force and carelessness. While large and heavy objects can be handled with a power grasp allowing use of large grip forces. The pinch grip or precision grip (Napier, 1956) is a frequently used technique generally consisting in the opposition of the thumb and index finger to form a grasp; the object is squeezed between the tip of both digits. It has been demonstrated that object surface's properties influence the contact phase of prehension (Westling & Johansson, 1984) by providing haptic information programmed by the CNS to adapt finger grip force (Forssberg et al., 1995), but also the approach motion (Fikes et al., 1994). Forssberg et al. also demonstrated that object properties are analysed through vision to adapt grip force in advance of contact. Therefore, object properties affect the contact phase but also the pre-contact phase. A better understanding of this can help design engineers in developing products answering the need of people experiencing difficulties when handling items, such as older people. Fikes et al. found that people took more time approaching slippery objects, to which Flatters et al. (Flatters et al., 2012) added that object surface's properties do not solely affect the pre-contact phase's movement time but its entire structure; differentiating 'stop-and-go' and ‘fly-through’ movements. Changes in the object’s size and surface friction affect the proportion of ‘fly-though’ movements.

These two distinct movements were first observed by Mon-Williams and Bingham (Mon-Williams & Bingham, 2011). They showed that to pick an object off a tabletop, people would either stop next to the object to position accurately their grip or simply reach, grasp, and lift the object in a continuous motion (i.e., ‘fly-through’). Any skill, or higher-order action, is the result of a combination of movement patterns, or lower-order movements. The selection of the movement pattern is made by ‘inverse models’; they are neural circuits that once activated by a given input stimulus produce the desire movement (Wolpert & Ghahramani, 2000). These models are believed to have a common neural architecture and to be mostly located within the brain. Learning a new skill is the result of the modification of an existing neural circuit into a new one fitted to a specific environmental demand. A higher-order behaviour results therefore from the combination of many lower-order movements occurring sequentially or concurrently. A small variation in the environment, with no apparent repercussion on the action, can activate different inverse models, provoking a different action. Behaviour flexibility and adaptability to environment changes is the result of the possibility to combine many lower-order actions in countless ways. ‘Fly-through’ and ‘stop-and-go’ motions are therefore respectively the concurrent and sequential organisation of reach, grasp, and lift actions (the three separated actions forming reach-to-grasp-and-lift). These organisations can be predicted more accurately when the combination of actions is selected from the onset and not adjusted as the movement unfolds (Flatters et al., 2012). The ‘stop-and-go’ motion implies a safer and more cautious way of picking the object up. More cautious, hence safer behaviour has been observed by Flatters et al. with slippery and wide objects (Flatters et al., 2012), proving that product properties can induce safer behaviour.

Quantitative and qualitative relationships between movement structure, object properties and location have already been identified (Fitts, 1954; Flatters et al., 2012; Mon-Williams & Bingham, 2011; Mon-Williams & Tresilian, 2001; van Bergen et al., 2006). In its main part, this thesis focuses, through the analysis of kinematic parameters, on reach-to-grasp-and-lift actions' pre-contact phase with respect to age. Despite the presence of a study on pinch grip contact phase, large consideration is placed on reach-to-grasp, because it is a prerequisite for successful manipulation, and affects the movement and grasp efficiency. The work presented here is an extension of the work done by Flatters et al. (Flatters et al., 2012), where they demonstrated how, in a reach-to-grasp movement, the alteration of object properties such as surface coefficient of friction, object distance from actor, and object size changes the actor's pre-contact movement.

Reach-to-grasp actions can be affected by many product characteristics whether the person is young or older. While characteristics such as temperature (Carnahan et al., 2001) and weight (Westling & Johansson, 1984) are known to have an important effect on forces application during grasp, object width, distance, and friction were chosen for this study, because they were shown to be significantly influencing the pre-contact phase of users' reach-to-grasp actions' (Flatters et al., 2012), and have been favoured by literature. Literature has especially favoured object's surface friction, because it has one of the most significant influence on grasp stability, and consequently on people's reach-to-grasp approach. Because those characteristics guide the finger grip aperture people use, their wrist positioning approach, and speed, they will determine accurate targeting and help collisions avoidance of any reach-to-grasp action. Reach-to-grasp actions are collision avoidance (Rosenbaum et al., 1999) and targeting tasks (Bootsma et al., 1994). These tasks are dependent of the width to be pinched between the thumb and index when no change is made to the size of the surface areas (Mon-Williams & Bingham, 2011). Finally, Flatters et al. showed how young people adopt a 'fly-through' or 'stop-and-go' motion depending on the object width, surface friction, and object distance.

During the analysis of reach-to-grasp movements, the kinematic measures analysed are: peak speed (PS); time to peak speed (tPS); normalised time to PS (ntPS); maximum grip aperture (MGA); time to maximum grip aperture (tMGA); normalised time to MGA (ntMGA); proportion of 'stop-and-go' movements (stop); dwell time (dwell); and movement time (MT). These kinematics are illustrated in Figure 2.5. The first aspect of a movement one might think of measuring is the actual duration of such movement, the time taken by people between the initiation of their movement and the point they grasp the object, hence MT. Consequently, the velocity of the hand is crucial to know whether people reach the object rapidly. The determination of tPS mark the acceleration and deceleration phases revealing how early one starts slowing down their approach. Caution and dexterity are reflected in the aperture one creates and especially in the margin with the object width. Similarly to tPS, tMGA divides the motion in two, where a long aperture-closing phase would highlight a more careful approach. Finally, care taken or the difficulty encountered are emphasised by a 'stop-and-go' movement, and the length of time spent adjusting grip before lifting the object. Jeannerod observed that MT does not fluctuate with distance for complex movement executed without enforced time constraints. (Jeannerod, 1984).

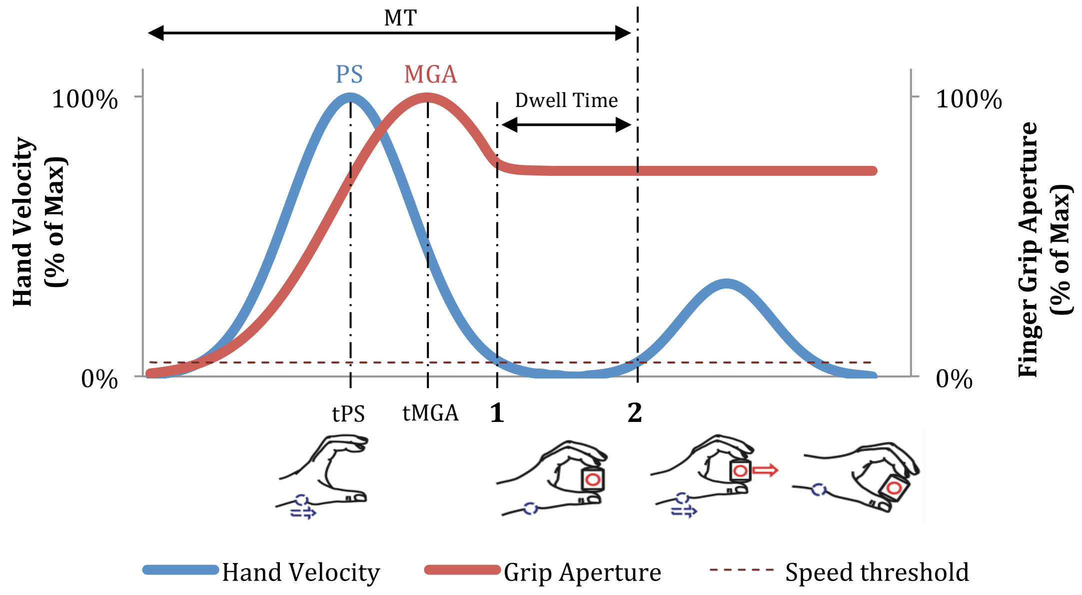


Figure 2.5 Kinematic profile for 'stop-and-go' prehension movement, representing Peak Speed (PS), Maximum Grip Aperture (MGA), Movement Time (MT), time to Peak Speed (tPS) and MGA (tMGA), and Dwell Time. 1, the hand velocity drops below the threshold velocity; the object has been reached. 2, the hand velocity exceed the threshold velocity; secure grasp has been achieved and the object is set in motion.

To completely analyse the reach-to-grasp-and-lift movement, additional work is presented in this thesis on the contact phase. Extensive research already exists on grip force application while handling an object in a precision grip. However, no research had been found to jointly study grip force variation with aperture width and object surface's friction. Although most of the literature draws the evolution of grip force in static squeezes or in smooth handling movements, there is evidence that when expected and unexpected inertial loads are suddenly added onto the object, people rapidly increase their grip force to maintain a high grip force safety margin (Eliasson et al., 1995; Johansson, R. & Westling, G., 1988; Kourtis et al., 2008). People's reaction to sudden and unexpected perturbations is studied in this thesis by observing the grip force people use relatively to their maximal capacities to cope with a sudden increase in inertial loads.

2.2.4 Forces in Action in a Grasp

As seen in Section 2.2.2, an important part of a successful grasp originates from the anticipatory control of the internal model that has been built through previous experiences. In voluntary manipulation, feedforward force control is more important than sensory feedback (Blennerhassett et al., 2006; Flanagan, J. R. & Wing, A. M., 1997; Jenmalm et al., 2000; Kourtis et al., 2008; Nowak et al., 2004; Nowak & Hermsdorfer, 2003; Nowak et al., 2003; Sarlegna et al., 2010; Smith & Soechting, 2005). Prior knowledge is so important that in hypergravity grip force is overestimated when moving the object, because the relation between weight and mass is not what the mind is used to (Lefevre et al., 2010). However, cutaneous feedback allows a more efficient grip force by giving precise information to the brain on the coefficient of friction between the skin and the object surface, and on the object's weight (Augurelle et al., 2003; Flanagan & Beltzner, 2000; Monzee et al., 2003).

Grip force is influenced by the coefficient of friction between skin and object surface, the object's weight and shape, the cutaneous afferent sensory feedback, and the internal model of dynamics (Jenmalm et al., 1998; Johansson, 1998; Kinoshita & Francis, 1996; Lefevre et al., 2010; Westling & Johansson, 1984). The grip one applies on an object must induce frictional forces opposing the gravitational force in order to lift the aforementioned object and prevent slippage. When the object is handled, moved, or carried while the subject is on the move, inertial forces materialise with movement acceleration (Flanagan & Tresilian, 1994; Gysin et al., 2003). The normal and tangential components of the force exerted by a digit on the object, respectively referred to as grip and load force (vertical lifting force), fluctuate in parallel to counteract those inertial forces and keep a safety margin for a secure grip (see Figure 2.6) (Flanagan & Wing, 1995; Johansson & Westling, 1984). The efficiency of a grip is therefore measured by the ratio of the grip force over the load force.

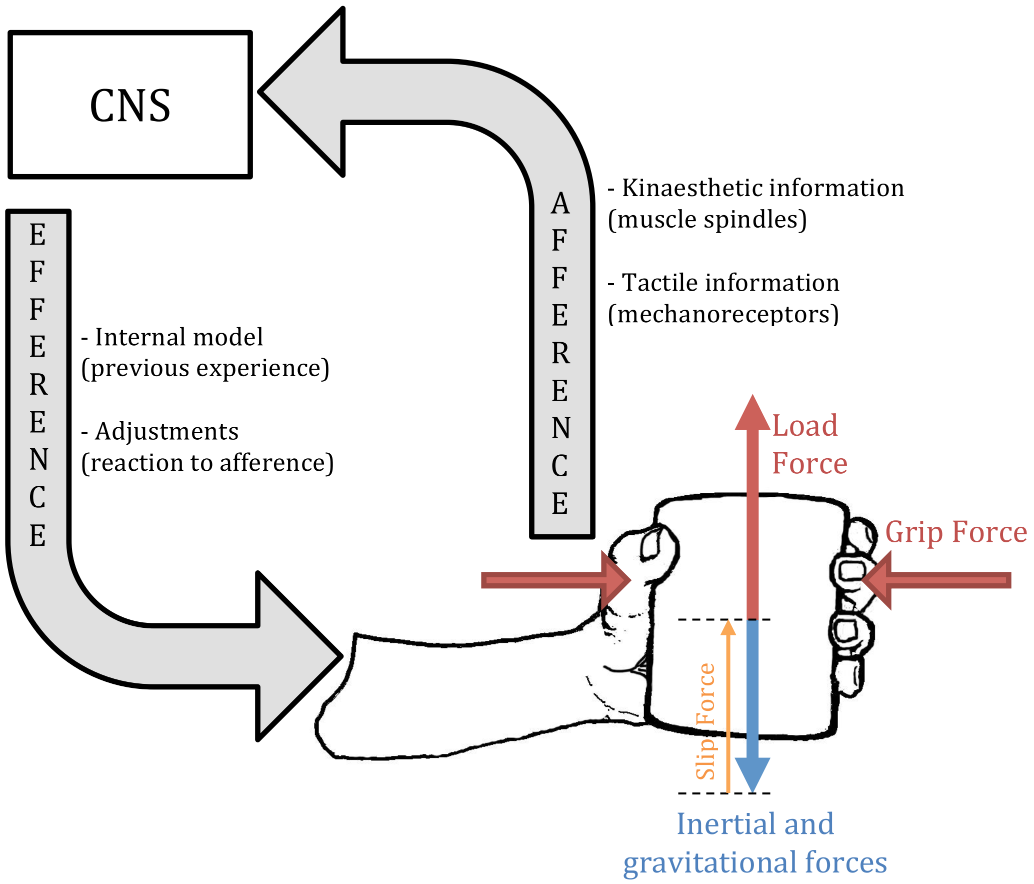


Figure 2.6 Forces in action in a stable grasp, and the information transferred to and from the Central Nervous System (CNS) to conserve that stable grasp. The grip force and load force fluctuate in parallel to prevent the object from slipping out of grasp. The slip force is the minimal force counteracting the inertial forces to prevent slippage.

The minimal grip force that can be applied on an object before it slips out of grasp and falls is often referred to as the slip force. "*For the object not to slip off the hand, grip force must be adjusted. Coordination of grip force and load force therefore depends on a combination of sensory and predictive processes, and those might be impaired in older people*" (Gilles & Wing, 2003). Too small a grip force would let the object slip, while too large a one would induce fatigue in the fingers and could damage the object. To get around this, people apply a grip force slightly larger than the minimal force required to prevent slip, thus creating a small safety margin between the grip and slip forces (Johansson & Westling, 1984; Westling & Johansson, 1987). This force mostly depends on the object's weight and contact area's coefficient of friction. This margin greatly depends on one's cutaneous sensitivity and internal model accurate estimation. It is an excellent representation of the efficiency of someone's grip. An accurate grip force is the result of a good estimation of the object properties by the CNS, and of an efficient work from the mechanoreceptors in informing the CNS. The latter can be misled by factors such as temperature and gloves. Indeed a cold object is perceived as more slippery than it actually is (Carnahan et al., 2001), while gloves reduce tactile sensitivity forcing a higher grip force and force rate development (Buhman et al., 2000; Shih et al., 2001; Tsaousidis & Freivalds, 1998).

The slip force depends on the object's properties, but particularly on its surface finish, and more precisely on the coefficient of friction between the skin and the object's surface. The object friction and the skin friction form this friction coefficient; it is still debated today whether skin hydration and skin friction are affected by ageing and would be the cause of higher grip for older people (Andre et al., 2011; Gerhardt et al., 2009; Gilles & Wing, 2003). The reasons for the differences in grasping and lifting between young and older remain uncertain.

2.2.5 Power Grip

Precision grip is more straightforward to tackle than power grip, because it consists solely of two contact points. Both digits are applying a force on the object at their respective contact point; in a stable grasp the two resulting force vectors are opposing one another. In all the research cited, the study of pinch grips has been simplified into the study of two force vectors at the contact area: load and grip force, being respectively tangential and normal to the contact area. Power grip is more complicated to represent as it consists in more than two contact points. Indeed each digit or even phalange can be in contact with the object grasped and apply a force; even the hand palm can be involved in the grip. Furthermore, all the resulting forces are not collinear and can be directed in an infinite number of directions. The size, and shape of the object have therefore paramount importance in the force distribution as they can affect the positioning of the hand. Finally, the task to be performed with the grasped object also impacts the power grasp's forces application and positioning of the hand. For instance, in a pinch grip, gravitational forces are counterbalanced by the frictional forces induced by the grip forces, while in a power grasp, the object can, in general, be entirely enclosed in the hand, and grip force can be directly opposed to gravitation without the need for frictional forces.

Grip span has a significant effect on people's grip strength capacities (Petrofsky et al., 1980), but different strengths, different hand sizes make the existence of a universal handle for all impossible (Buchholz et al., 1992; Grant et al., 1992). The optimal handle size, where maximal grip force strength can be reached, is a function of individual anthropometric data. Some have tried to express grip strength as a function of hand dimensions (Freund et al., 2002; Li et al., 2010). Grip force was found to be dependent on the hand circumference and the diameter of the grip, hence the handle diameter. Understanding the relationship between handle diameter, perceived comfort, and finger force distribution has been researched using much diverse sophisticated equipment with force sensors embedded in gloves (Kong & Lowe, 2005), or handles (Seo & Armstrong, 2008; Wimer et al., 2010), or by directly taping them onto the skin (Pylatiuk et al., 2006). Kong and Lowe give a ratio between hand sizes and handle sizes for best efficiency, and observe the force distribution between all the phalanges. Pylatiuk et al. stipulate that fingers force distribution to perform a task greatly fluctuates with the necessary prehension pattern. They also suggest that finger forces in power grasp seem to be influenced by gender but unlike pinch grip not by hand size or age. Therefore, it is difficult to extend observed power grip facts to handles of different diameters and shapes. In addition to that shear force plays a far more important part in a power grasp than it does in a pinch grip (Enders & Seo, 2011). Measuring grip force in power grip is therefore an arduous task requiring complex and sophisticated equipment.

The sense of touch gives important sensory feedback allowing the hand to apply the necessary amount of force, and adapt it to environmental changes, such as load force or texture variations. As seen for a pinch grip, human beings rely on this feedback given by the high sensitivity of hands. However this sensitivity is not evenly distributed over the whole hand. Due to its lower receptor density the palm has a detection performance six times lower than fingers (Craig & Lyle, 2001). And yet both fingers and palm process tactile information in the same way, resulting in no fundamental changes in tactile perception processing between a pinch grip and a power grip (Picard et al., 2003). Nevertheless, understanding afferent signal for a pinch grip is hard, understanding it for a power grip is even harder.

2.2.6 Age and Grasp

"*The most widespread example of decreased motor ability arises not from distinct pathological syndromes but rather from the normal ageing process.*"(Cooke et al., 1988). Cooke's study showed that when performing movement at two different speeds the older people had similar averaged speed and movement duration as the young cohort, but exhibited more individual variability. He admitted however that the task did not require enough accuracy to observe slower movements from the older people, as it is then that differences appear. The question though remains whether older people's pre-contact phase is influenced in the same way as the one of young adults, and if not, whether it is solely the results of lower hand dexterity.

While the kinematics of the pre-contact phase of a reach-to-grasp-and-lift for older people remains unclear due to the small amount of research present, the grip force applied by older people remains unclear due to the contradictory researches present. Most agree that older people apply more force when grasping an object than their younger counterpart. Yet while Gilles and Wing found safety margin similar for older and younger adults (Gilles & Wing, 2003), Cole et al. found it twice as large for older (Cole et al., 1999). In addition Gilles and Wing observed that older people's higher grip force is just a compensation for their lower skin's coefficient of friction (Gilles & Wing, 2003), and according to Comaish and Bottoms, their skin has a lower coefficient of friction because of its lower hydration (Comaish & Bottoms, 1971). Kinoshita also observed higher safety margins and more slippery fingers with older people (Kinoshita & Francis, 1996). On the other hand Gerhardt states that older people do not have lower skin friction, but lower elasticity and higher skin hydration (Gerhardt et al., 2009). Gilles and Wing also demonstrated that older people apply more grip force during static and dynamic holding than young. With similar findings Kinoshita revealed though that there is a large fluctuation in grip force data with older adults. However grip force modulation is synched with load force fluctuation for both populations, meaning that when the load changes the grip force changes accordingly. Also both populations apply more grip force on smooth surfaces than rough ones, and older people adapt just as well to different surface textures and variation in load force. Manual dexterity is reported to be worse for adults in their 60s and 70s than for young adults. Moreover, it has been reported that older people are more variable in arm movement tasks (Cooke et al., 1988). Bland et al. found that older people took more time to complete the Jebsen test (dexterity test), but were similarly affected by a restricted active range of motion (Bland et al., 2008). Additionally age, gender, wrist position, forearm position, hand tested, and gloves may affect wrist torque.

Grip force is also commonly known to be significantly weakened after a stroke or by arthritis and steadily declining with age after about 50 years old, (Frederiksen et al., 2006; Hackel et al., 1992; Lamberts et al., 1997; March et al., 1998; Mathiowetz et al., 1985; Rantanen et al., 1998). The ability to manipulate an object with the hands requires the ability to reach the object, and then grasp it by enclosing it and applying forces on it while avoiding slippage. It is thought that due to lower skin friction (Gilles & Wing, 2003; Kinoshita & Francis, 1996) older people might struggle more in such task and are forced to apply more force than their younger counterpart. As well as the loss of strength with age, hands are, with feet, the limb most affected by cutaneous sensitivity decrease (Stevens & Choo, 1996), making the person apply more force. This thesis thus aims to better understand the pre-contact and contact phase of the reach-to-grasp-and-lift movement of young people as well as older people, and observe the influence of product characteristics in order to help designing more inclusive products.

2.3 Conclusion

The population of developed countries is ageing. In 2031, 20 million people in the UK will be over 60. People are living longer but too much of that longer period of life is still considerable as unhealthy living. Without going to such extreme, even healthy ageing generates difficulties in daily living. People over 60 tend to be generally frailer, but this is no reason to exclude them from society. Humanly speaking the environment must be adapted to their capacities, and economically speaking the workplace as well since they are to work at later age to compensate for an ever-smaller active population compared to the retired one.

Literature has identified the main consequences of ageing: loss of sensitivity, physical abilities, and cognitive functions; all that defines healthy ageing. And all of it affects our ability to handle objects and interact with them. However the size of the literature on older people is still significantly smaller than their proportion in the global population. This all means that products must be adapted to older people and their lower dexterity, and that a lot needs to be researched to achieve such goal correctly. Too often design professionals create products with the able-bodied population in mind. Thankfully with the development of inclusive design, impairment simulators recreating the older users' experience are also being developed. ADL scales highlight that cooking and eating hold a large place in our daily life. Losing the ability to successfully achieve those leads to loss of independence. This loss of ability mainly comes from the inability to grasp, manipulate, and use kitchen utensils. All these actions use our hands. A human hand is a sophisticated body part, which works in a not less sophisticated way with the CNS to provide feedback on the environment but also to interact with it.

A stable grasp results from a successful hand approach and a successful grip force application. Both have been found to be affected by product characteristics. This thesis therefore analyses the kinematic parameters of reach-to-grasp actions on pinch and power grasps, and how they fluctuate with object properties and users' age. In addition, to further extend the already large literature on grip force, this thesis also investigates grip force variations with aperture width, object friction, and users' age on pinch grip. The grip force generated by the digits must generate frictional forces to counteract inertial forces and stably grasp and lift a product. This grip force generated informs on the user's capacities and efficiency.

This thesis is an attempt to develop the knowledge on the older people condition and provide a better understanding of grasp for younger and older adults. The outcomes are expected to be implementable into design guidelines to help designers in developing more accessible and confortable handheld tools.

Chapter 3

Methodology for Investigating the Influence of Ageing and Object Properties on Prehension

3.1 Methodology

Chapter 2 has shown that independent living greatly relies on people's capacity to cook and feed themselves. Emphasis was thus put on cooking and the kitchen environment. The Inclusive Design Group, part of Cambridge's Engineering Design Centre (EDC), states that to improve the inclusion of a product it is important to identify the excluded population and its size, but crucially the reasons for their exclusion. This thesis follows the same idea, and rather than imposing guidance to older people about what is best for them, it holds a great desire to know more about them.

The research work thus began with the collection of information on the older users to identify what causes the most difficulties for older people while using utensils to prepare food in their kitchen. Focus groups were therefore organised to give older people an active voice, and an opportunity to express their issues, perceptions, and ideas. Older people's comments, reported in Chapter 4, correlated with the literature in accentuating the importance of good grasp capacities for cooking. The knowledge acquired with these open discussions with older people, combined with the observations derived from the literature steered the research into its final path.

The aim of this thesis, as identified in Chapter 1, is to investigate the interaction between products and users by inspecting the effects of product characteristics on people's prehension. The present research looks into the effects of product characteristics on reach-to-grasp movement and grip force applied to secure a grip on a younger and an older adults population. The analysis of reach-to-grasp-and-lift actions was first organised around precision grip, and later further extended to power grip.

This thesis' experimental work therefore began with the investigation on the effects of those characteristics on pinch grip reach-to-grasp actions for younger and older people, trying to answer the first research question (RQ.1): ***Does age affect the way individuals adapt their reach-to-grasp movements to changes in object size and friction?*** Chapter 5 reports the study that was run to answer that question, and scrutinize people's movement by analysing a wide range of kinematics that dictate it.

As mentioned earlier, a successful grip results from an accurate reach-to-grasp approach, but also from a proper application of grip forces. The contact phase naturally follows from the approach phase; here the dominant metric is the grip force people can generate to secure their grip, and lift the object. In the continuity of Chapter 5's study on pinch grip reach-to-grasp, Chapter 6 focuses on pinch grip forces and the effects of object size, surface friction, and users' age. It evolved from the second research question (RQ.2): ***Does age affect the way object size and friction limit the maximum force that individuals can apply to a given object?*** The maximal pinch grip force one can apply on an object, in other words one's pinch grip force capacity, is not necessarily the force used to handle a given object. For that reason Chapter 6 gathers first a study where maximal pinch grip force is measured on a fixed object, and secondly one where peak grip and slip forces are measured during a lift subjected to a perturbation.

Loss of hand dexterity is a common consequence of ageing, often critical for people with arthritis. An answer to the following research question is one way of verifying whether reduced hand dexterity is an importantly influential factor on older people's behaviour, provided that answers to the previous two research questions show any age effects (RQ.3): ***In what ways, if any, do impairment simulation gloves replicate these effects?*** As mentioned in Chapter 2, CISG are low hand dexterity simulators, and might therefore also be effective simulators of older people's behaviour. The present work's interest in CISG is in identifying whether they can force a younger population into adopting reach-to-grasp-an-lift actions similar to an older population. Therefore in addition to the analysis on reach-to-grasp actions and grip forces for younger and older adults, testing on reach-to-grasp actions and grip forces for young adults wearing CISG was added respectively in Chapter 5 and Chapter 6. These two chapters revealed that while, like age, reduced hand dexterity does not influence people's grip force, it forces young adults to adopt reach-to-grasp movements close to the ones of older adults. However, young people did not stop more of their approach to secure their grip, and not being used to such condition suffered a high density of failures. This shows that lower dexterity requires greater care, and that the strategy adopted by older people is potentially an attempt to remain effective.

As said earlier, once the effects of ageing, object size, location from user, and surface friction had been observed for a pinch grip, they could be studied for a power grip. As detailed in Chapter 2, power grasp is a crucial technique as it allows the application of a large amount of force. It is likely to be the most relied on technique when handling kitchen utensils during food preparation; heavy tools, tools with handles, large tools, all require to be grasped with the entire hand. Therefore while the fundamentals are based on pinch grips, research on power grip is necessary to inspect whether similarities exist in reach-to-grasp motions between pinch and power grasps. This task is approached in Chapter 7 by the fourth and last research question of this thesis (RQ.4): ***Do the influence of object size, object friction and age on reach-to-grasp actions with a pinch grip generalise to those using a power grip?*** Once adapted to kitchen pans, the study of Chapter 5 was reproduced in Chapter 7 to observe the evolution with age of people's reach-to-grasp for power grasps. The friction and object distance conditions were identical, while the object widths no longer related to object length but rather to the cylindrical handle's diameter.

In accordance with the rest of this thesis, this chapter studies the effects of healthy ageing, because ageing is known to affect performances. Similarly to the other chapters, since a larger age gap is likely to reveal a larger difference, subjects part of the younger cohorts were selected to be younger than 40, while the older subjects to be over 60 so to maximise the chances of observing divergences. Additionally, it is hypothesised that one major consequence of ageing is the loss of dexterity. As a consequence young adults wearing CISG took part in the experiments to observe the effect of hand dexterity losses on grip force capacities evolution with object size and friction.

3.2 Grasp Force Vectors

A stable grasp is reached when the object is securely held immobile between digits. The grasp, or contact phase, is thus defined by the forces in action on the object. As seen in Chapter 2, object properties affect grip force, and thus the stability of a grasp, which will consequently affect the reach-to-grasp approach. The interaction between the user's digits and the object at the points of contact is therefore crucial. This section explains this thesis' understanding of pinch and power grasp forces distribution during contact.

3.2.1 Pinch Grip

Static Friction

Newton's third law stipulates that the force exerted by a body onto a second body is of equal magnitude and opposite direction to the force exerted by that second body onto the first (Figure 3.1).

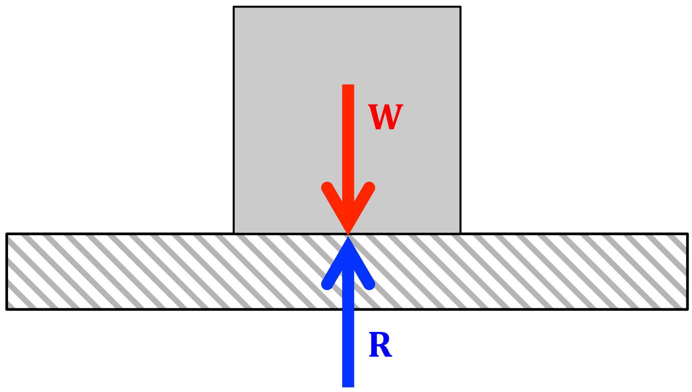


Figure 3.1 Diagram explaining Newton's third law. The reaction force (R) exerted by the supporting board onto the block is of equal magnitude and opposite direction to the force (W) exerted by the block onto the board.

There is static friction between two objects in contact when they are not moving relatively to one another. In such case, the frictional forces prevent sliding between the two object surfaces. The frictional forces at the contact area between the two objects are dependent on the normal force and the coefficient of friction. A normal force is exerted by each surface on the other, and directed perpendicularly to the surface. The coefficient of friction is defined by the two materials in contact. For an object, of a given mass and material, on a titled surface, of a given material, the point at which the object starts sliding is solely determined by the titling angle of the surface.

A mass on the titled surface applies its weight vertically on the surface (F), which applies in reaction a force of equal magnitude and opposite direction (R). The reaction force can be decomposed into a component normal (R_N) to the contact area, and one tangential (R_T) to it. While R_N stops the object from sinking into the surface, R_T is the frictional force counteracting potential sliding. The condition that would lead to sliding is governed by Coulomb's friction law. It states that as long as the frictional force R_T remains smaller than the product of the normal force R_N and coefficient of friction (μ), the object will remain stable and not slide, hence $|R_T| \leq R_N \cdot \mu$ (Fearing, 1986; Mason, 1982). This equation can be geometrically represented by a cone of friction. The cone of friction includes all the force vectors for which the tangential component would not be large enough to initiate slip. The top of the cone of friction is located at the contact point, and its axis of revolution is centred along the axis normal to the object's surface at that contact point. The generated cone has a cone angle ψ_S and a half-angle Φ_S, where $\psi_S = 2\ \Phi_S$. The reaction force (R) forms an angle $\alpha = \tan^{-1}(|R_T|/R_N)$ with the axis normal to the contact surface at the contact point; equal to the wedge angle of the surface the object rests on. As it can be observed in Figure 3.2, the condition of friction necessary to avoid slip is $\alpha \leq \Phi_S$, where $\Phi_S = \tan^{-1} \mu$ (Mason, 1982), which falls back on Coulomb's equation: $\mu \cdot R_N \geq |R_T|$. If R_N decreases and R_T increases to the point where α becomes larger than Φ_S then frictional forces can no longer prevent slip; the object moves then against the surface. On the other hand if the vectors R and F are kept constant, the mass remains immobile on the support's surface as long as the wedge angle (α) is lower or equal to the half-angle of the cone of friction (Φ_s) (see Figure 3.2).

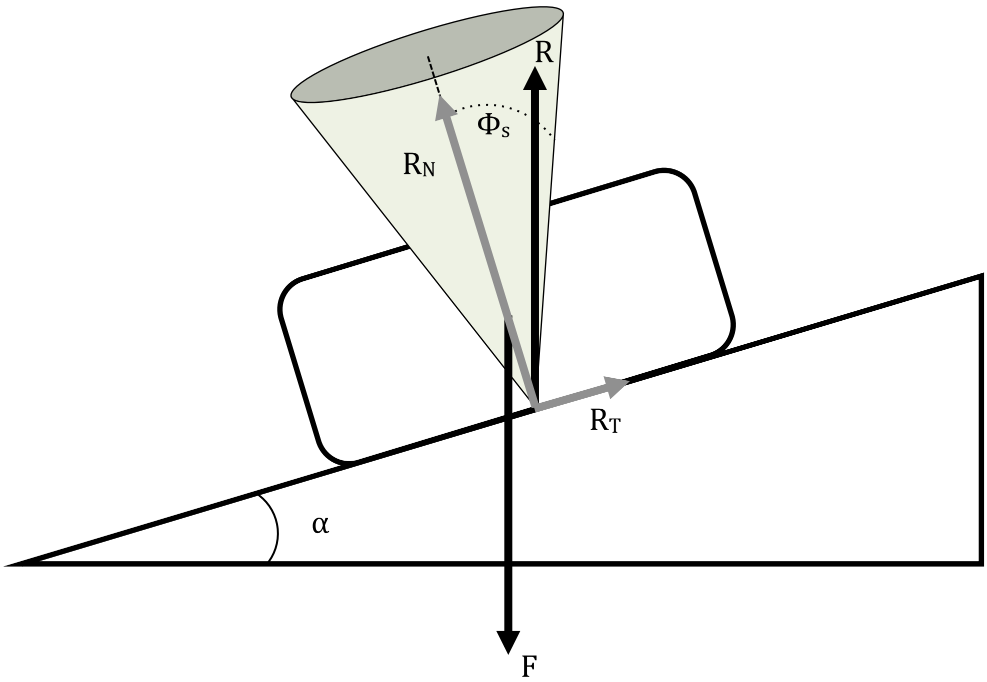


Figure 3.2 Stable static conditions of a solid's weight on a wedge surface.

It becomes evident that the coefficient of friction bears a more important role in the mass stability with greater inclination angle. The inclination of the wedge surface amplifies the effect of friction by bringing R closer to the edge of the cone of friction. For that reason, the grasp surface of the objects used in the pinch grip experiments of this thesis were curved; fingertips can hardly apply a grip force normal to the surface. Indeed the theoretical approach detailed in this section can be applied to the contact area between the fingertips and the object pinched.

Pinch Grip Force Application

In the pinch grip experiments the objects to be pinched were made out of Nylon. It is a material easy to machine, light, and hard enough not to be damaged if dropped or squeezed too hard. They were cylinders of different length to test the effect of width, and had to be pinched by their ends, which were curved to amplify the effect of friction. The cylinders rested on a support on their side keeping their axis of revolution parallel to the tabletop. When squeezed between the thumb and index finger in a stable grasp, the forces exerted by both digits are collinear, of equal magnitude, and opposite direction. The work on pinch grip that follows is based on the assumption that the force axis (i.e., axis along which each finger grip force is applied) is parallel to the cylinder's axis of revolution (Figure 3.3). This assumption is tenable firstly because it is the most stable technique, which intuitively people will try to adopt. Due to the curvature of both contact areas, an increase in angle between the forces and the cylinder's axes would result in an increase in grasp instability. Secondly the contact areas are small on both sides limiting the deviation angles to tiny degrees of amplitude. Finally, due to the symmetry of the object to be pinched, the forces distributions are similar for both fingertips.

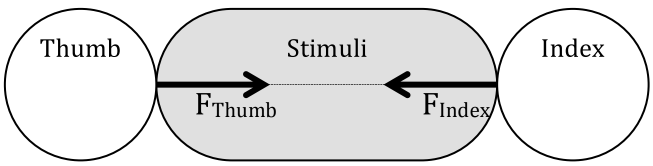


Figure 3.3 Forces applied by both the thumb and index finger at the apexes of the curved ends of the stimuli. The force applied by the thumb (F_{Thumb}) is of equal magnitude and opposite direction to the index force (F_{Index}).

The object made of Nylon cannot be deformed by the sort of forces being applied in these experiments. In this representation of pinch grip forces, fingertips are represented as circular fingers (Figure 3.3) with negligible deformation due to the small area of contact. It is accepted that there is therefore a unique contact point between the fingertip surface and the convex surface of the object. The actual deformation would result in some change in friction coefficient and would allow the ability to generate torque to prevent rotation, but in general terms the deductions from the simplification still apply. Even spread over an area, the average force still acts at a given point. Within this set of forces some are acting at a shallower angle and some at a greater angle. Although this slightly improves the stability of the grasp, it does not change the fact that the further off-centre fingers are, the harder the object is to grasp. Additionally, it does not solve the difficulty due to inability to enclose the object. The normal component of the grip force is collinear to the convex surface's radius at the contact point, and the tangential force is coplanar to the plane tangential to the object surface at the contact point.

The theoretical force system at the contact point between a fingertip and an object corresponds to the force system sketched in Figure 3.2. The force exerted by a finger on an object at the contact point can be decomposed into a force normal to the surface (F_N) and one tangential to the surface (F_T), similarly to R_N and R_T from the previous subsection. A secure grip implies that the object is not slipping. For that, the tangential force resulting from object's surface friction, is constrained to be no greater than the product of the normal force due to object stiffness, with the coefficient of static friction, hence $|F_T| \leq F_N . \mu$. In this unique situation where finger forces are applied at each apex of the grasp areas, then the contact surfaces on both sides of the stimuli are parallel. In any other case there is an angle between the two contact area planes. The system representing the studied cylinders pinched by their two curved ends can therefore be represented by an extension of Figure 3.2 to a double wedge support. In the situation where the object is wider than finger aperture no digit can apply a force at an apex. As a consequence both digits' R_T forces are pointing outward the hand, due to the curved surfaces. If the digits start to slip the object is thus pushed out of grasp.

In all the pinch grip experiments of this thesis, both ends of the cylindrical objects to be pinched had identical curved surfaces. A curved surface results in the application of a force at a distance d from the centreline of the radius (also corresponding to the cylinder's axis of revolution). As mentioned above, each finger has a single contact point with the object. If $d = 0$ then the grip force is applied at the apex of the rounded end. At every contact point the object's reaction force (R_N), normal to the object's surface, is along the cone of friction's revolution axis. The cone's half-angle Φ_s is defined by the surface material, and is therefore constant across the entire rounded end. Any force applied on the object will be at an angle α from R_N; when $\alpha = \Phi_s$ the force lies at the limit of the cone of friction ($F = F_{lim}$). Slip will occur as soon as $\alpha > \Phi_s$. For a given force vector F_{lim} lying at the edge of the cone of friction correspond a distance d_{lim} from the cylinder's axis, where $d_{lim} = r \,.\, \sin(\Phi_S) = r \,.\, \sin(\tan^{-1} \mu)$, where r is the radius of the cylinder's end curvature. Keeping F_{lim} constant while displacing its contact point by increasing d, so that $d > d_{lim}$, would result in F_{lim} lying outside the cone of friction (as seen in Figure 3.4). Therefore Φ_s and d_{lim} are linked to the surface's coefficient of friction μ. Increasing μ increases Φ_s and thus the volume of the cone of friction, it also increases d_{lim} generating a larger functional area which can be grasped to achieve a stable grasp.

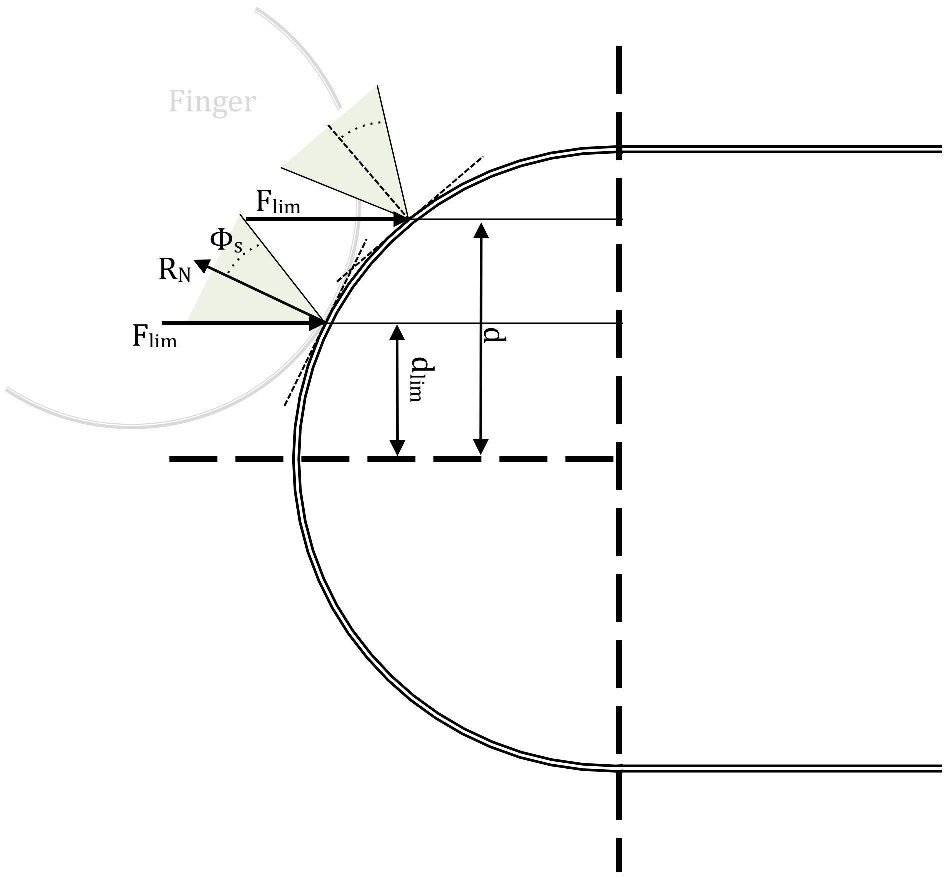


Figure 3.4 Application of a force F_{lim} on a curved surface with a cone of friction's half-angle Φ_S. To F_{lim} correspond a distance d_{lim} from the centreline, where F_{lim} lies on the edge of the cone of friction. If F_{lim} is kept constant and applied at a distance $d > d_{lim}$ then F_{lim} lies outside the cone of friction; slip occurs.

In summary, to avoid slippage grip force can only be applied within a certain functional area centred on the curved surface's apex. The size of this area is specific of the coefficient of friction of the skin/object surface. Increasing the coefficient of friction of the surface of the cylinder's curved ends increases the angle of the cone of friction, which increases the functional area, which in turn increases the width range in which a stable grasp can be achieved. Therefore rougher surfaces permit a wider range of force application patterns. For a given hand size, rougher surfaces offering a larger stable grasp surface will permit the grasping of wider objects. This all suggests that wider and more slippery objects are more difficult to securely grasp, because their stable grasp area is reduced. People have therefore less grip force patterns accessible to them for a stable grasp on those objects. As a result it is hypothesised that object width and surface friction bears an important role in people's grip force capacities, and grip force use during pinch grip. Furthermore, as a consequence these two product characteristics are thought to have a significant influence on people's reach-to-grasp actions as well.

3.2.2 Pinching and Lifting

Once an object is securely grasped, it can be lifted and carried around. If the conditions stated above are met, and frictional forces stop the object from slipping out of grasp, then inertial forces must be applied on the object in order to counteract its weight, and lift it. The forces that counteract gravitational forces are referred to as load forces and are applied tangentially to the object's surface. The pressure of each digit at each end generates a load force at both contact points. The grip and load forces, being respectively the normal and tangential component of the fingertip force applied by a digit on an object, fluctuate in parallel (Forssberg et al., 1991). If additional inertial forces are applied on the object, such as acceleration or perturbation during handling, both forces are adjusted to cope, prevent slippage, and conserve a secure grip on the object. As long as the perturbing forces are below the maximum frictional forces that can be generated, the object stays securely gripped. In a simple vertical lift, where there is no desire to accelerate the object laterally, the perturbing force is entirely vertical, and finger forces are of equal magnitude and opposite direction.

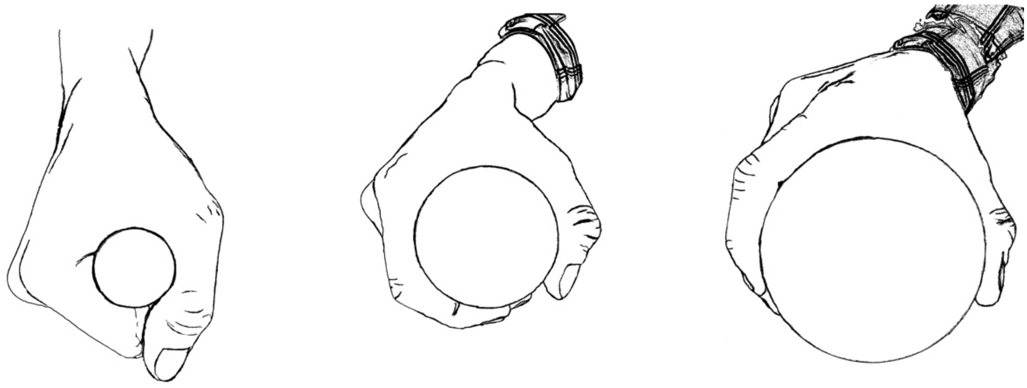
Going back to the wedged surface in Figure 3.2, increasing fingertip grip force while keeping its orientation constant would mean increasing F, which would results in the increase of R, and consequently R_N and R_T. As the proportion between the normal force component and the tangential force component is kept constant, R remains within the cone of friction. The increase of F has therefore not made the system less stable, however it has increased the frictional force (R_N); a larger oppositional force is necessary in order to force the object to slide. In effect, if the fingertip force orientation is kept constant but its magnitude is increased then the tangential frictional forces preventing it from slipping are increased. This means a more secure grip, but also explains why more pressure must be applied to heavier objects. Indeed more frictional forces must be generated in order to counteract larger gravitational forces.

Oppositely, when fingertip forces are reduced, the load forces are reduced, and only smaller weights and inertial forces can be counteracted. For a given object and a given hand there is a point where finger forces are no longer sufficient to counteract weight and retain a stable grasp on the object. The object therefore slides against the fingertips and slips out of grasp; the minimal finger force necessary to prevent any slippage is referred to as the 'slip force'.

In the demonstration detailed above, pinch grip had been represented by two circular digits, which only present a single contact point each with the object. The assumptions made to analyse a pinch grip in such way have been demonstrated in Section 3.2 to be tenable. However it is not the case for a power grip, as it relies in general on the entire hand instead of solely two fingertips.

3.2.3 Power Grip Force Distribution

A power grip is a more powerful and secure grasp technique than a pinch grip as it offers a larger contact surface and a wider range of forces. It however lacks the precision of a pinch grip. While a pinch grip consists in a two digits squeeze, a power grip generally calls for the use of every phalange of all of the five digits conjointly with the hand palm. In this thesis, only reach-to-grasp motions were studied for power grip, and not grip force. The three cylindrical objects used in this thesis' power grip study had significant different diameters, and therefore forced different power grasp contact systems, as seen in Figure 3.5. Depending on the diameter of the object to be grasped the fingers and hand placements differ, which is likely to alter the direction, magnitude, and distribution of the forces the hand can apply on the object.



Small handle grasp Medium handle grasp Large handle grasp

Figure 3.5 Power grasp around the three cylindrical objects tested, where the same hand is used to hold stable each of the three objects.

In the case of a small handle, where the circumference is smaller than the sum of the thumb and index finger length (Figure 3.5), the object is entirely enclosed in the hand, the thumb is overlapping opposing fingers, and their fingertips are likely to get in contact with the hand palm. The user can apply forces over the entire handle's surface, but discomfort can be brought by the fingers getting in contact with the palm.

For the medium handle, where the circumference is larger by a little margin than the sum of the thumb and index finger length, the thumb is no longer overlapping any finger, but its tip can be in contact with the tip of other fingers. The grip adapted to such diameter allows a contact of all the phalanges, and space for finger placement (i.e., fingers and palm do not obstruct one another). As observed by the literature presented in Chapter 2, the diameter for which maximum grip force can be exerted stands within this range of sizes. There is a large contact surface between the hand and the object. Furthermore by almost enclosing the object the hand can apply forces all around the object, keeping it safely inside its grip; during lift finger forces can be applied against gravity.

As the handle diameter widens, and its diameter draws near the user's maximal grip aperture, the handle can no longer be enclosed. The power grasp can be simplified to a clamp between the thumb and the four fingers. As the forces from the hand are no longer distributed all around the object, it is thought that stable grasp rely here more on friction. It is hypothesised that this grasp can be identified to a pinch grip, where the object is clamped between the thumb and a single opposing finger. In the study of the pre-contact phase of reach-to-grasp actions for power grasps, the handle was grasped from on top. In such cases, and for large handles, no finger can directly apply a force against gravitation, and thus successful lifts greatly rely on friction. It can therefore be hypothesised that for wide handles forcing large hand apertures, a stable grasp requires a high coefficient of friction, and therefore a wide cone of friction as seen in Figure 3.6, or the handle is pushed out of grasp.

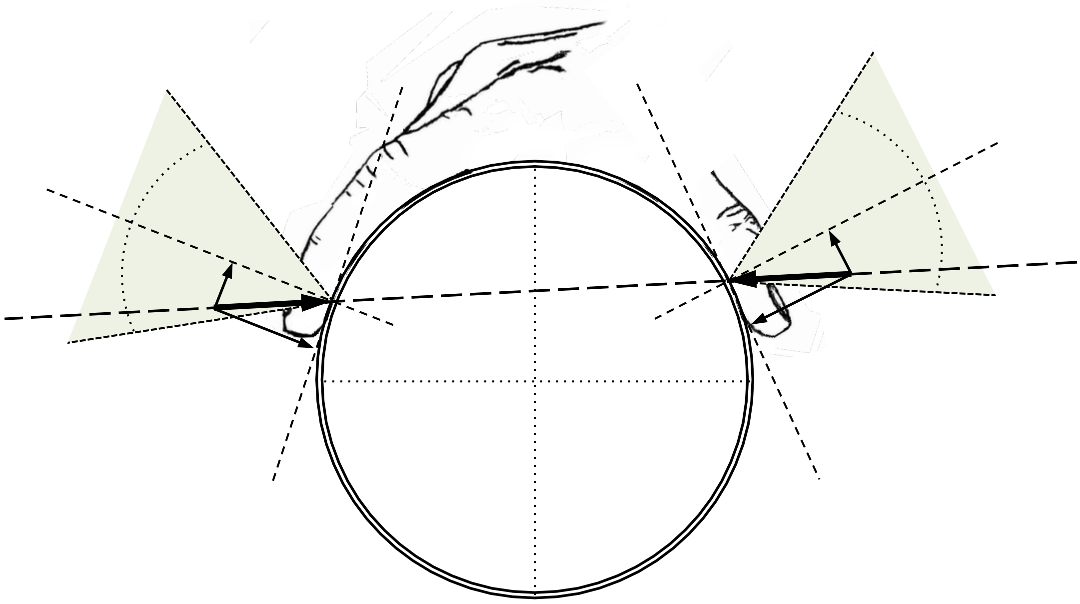


Figure 3.6 Simplified sketch of a power grasp around a wide cylindrical handle. In order for the frictional forces to retain the large object within the hand the cone of friction must have a large angle. Therefore the coefficient of friction must be high.

An object surface's coefficient of friction is paramount for pinch grips as well as power grips to secure a stable grasp. Nevertheless, when the hand can enclose the object in a power grasp, it is more in control since it can distribute forces all around the object; the importance of friction in grasp stability is lessened. However it seems that with large handles a power grasp can legitimately be represented by a simpler pinch grip, accordingly the object's friction becomes crucial.

Chapter 4

Focus Groups

User experience is at the heart of this thesis' research. Through a series of studies, grasping and handling were investigated to better comprehend the interactions between users and products. The effects that handheld tools' characteristics and designs have on people's handling of the latter are partly explored in this thesis. By better understanding the importance of products' characteristics influencing grasp, new design guidelines can be generated. More adequate products can follow from that, items that are more fitted to users, facilitating their experience. The ultimate goal is to improve people's everyday life by simplifying it and facilitating it by developing their environment. It is important for this research to have the biggest impact possible. For that it is important to base this academic work on concrete products and situations, and to pinpoint the needs, struggles, and desires of people. Care has been taken to avoid solely running intensively theoretical studies, lacking usefulness or practicality. The desire to correlate the work done and results obtained to real people's needs were in the mind of the researcher throughout the project. The interest was thus on getting users' perspectives, rather than a purely academic perspective, giving users an active voice, rather than making them passive subjects.

The specific user group of interest in this thesis work is the ageing population. In social sciences, researchers sometimes gather quantitative data to test hypotheses directly interviewing the people themselves. This can provide useful and important information on the end users, yet design professionals do not resort to it often enough. Additionally, as seen in Chapter 2**,** older people have not been sufficiently considered in product development or handling studies. It is evident that those studies are necessary and important, but enhancing people's product experience cannot be properly achieved if people are not questioned and heard. Consequently while the remaining chapters of this thesis focus on observing and measuring young and older people's reach-to-grasp-and-lift movement, the current chapter places the older people in the spotlight by inviting them to talk about their feelings and perceptions on handheld products, and their life in the home environment. The purpose of the organised focus groups discussed in this chapter was to allow older people to speak and be heard, and build on the research from the obtained comments.

By affecting one's mental and physical abilities ageing generally has an effect on the way people interact with their environment, hence on their handling and grasping behaviour. Age can bring limitations, which make task execution more difficult, possibly leading to an inability to perform. The writer believes that the ability to cook and feed oneself comes as a big part in independent living. Cooking is, to some extent, a difficult and hazardous task, and a kitchen can be a dangerous place due to knives, hot surfaces, and chances of liquid spillage. If as age related impairments develop, the kitchen environment becomes a hostile and dangerous environment then the ageing person will no longer be able to eat. Inability to cook or eat is likely to lead to depravation of independent living, since preparing a meal is an important task listed in ADL scales. Following that observation of the importance of keeping cooking possible and being able to deliver task accurately, product handling across adult lifespan was focused on a kitchen environment and illustrated by kitchen handheld utensil manipulation.

This chapter is divided into five sections. Section 4.1 describes the purpose of the focus groups, their methodology, and what came out of these discussions. Sections 4.2, 4.3, and 4.4 describe the protocol and results of three studies run in addition to the focus groups. The older subjects who took part in the focus groups, for the most part, took part in these additional activities. For the sake of comparison, young adults were recruited to also take part in the activities. These activities tested people's abilities, behaviour, and hand properties. Focus groups were not run with younger adults since the research was focused on older people's issues in the kitchen and their own perceptions. Section 4.5 discusses the obtained results to provide guidelines for the research undertaken in the remaining chapters by embodying older user's voice and apparent differences with young people. The sessions organised with older people were run conjointly between Leeds and Sheffield Universities, yet differences in research focus between the two universities reflected in the tests, as separated measurements were run by each university. The tests run by Sheffield were a Jebsen test, a grip strength test (using a Jamar dynamometer), a spatial discrimination test, and a friction test. The Jebsen test was not run in Leeds because the equipment necessary was bulky and could not be brought from Sheffield to Leeds. The tests reported here are solely the ones Leeds ran, being high-speed video recordings, hand size and wrist range of motion measurements, and a performance and dexterity test on a simple cooking task (i.e., Rice-pouring). For every session the number of participants who underwent each test is listed in Table 4.1.

Table 4.1 Table of the number of participants who took part in each test across all sessions run in Leeds and in Sheffield.

	University of Leeds				**University of Sheffield**	
	Session 1	Session 2	Session 3	Session Young	Session 1	Session 2
HSV Recordings	5	3	5	16	3	0
Anthropometry	5	3	5	16	3	0
Rice-pouring	5	3	0	16	3	0
Jebsen Test	0	0	0	0	3	0
Jamar Test	5	3	0	0	3	0
Spatial Discrimination	5	3	0	0	3	0
Friction Test	5	3	0	0	3	0

4.1 Focus Group

4.1.1 Subjects

People over 60 years of age were contacted through the University of the Third Age (U3A) in Leeds and Sheffield and through Age UK in Leeds. Those people were contacted by phone or email and invited to take part in a one-hour focus group session in groups of four or five. Three focus group sessions were organised at the University of Leeds, which brought a total of 14 older people (two men, and 12 women; age mean 70.25 years, age range 62 to 84 years), and two sessions were organised at the University of Sheffield, which added another six participants (demographic data collected for three participants of which two were women; age mean 64.6 years, age range 61 to 71 years). No demographic data had been retained for the second focus group session at Sheffield University, because the author was not present during that session and only received transcripts of the focus group discussion.

All participants provided informed consent prior to inclusion in the study. The study was approved by the University ethics committee. All participants were naïve with regard to the purposes of every study reported in this chapter. Participants were directly invited by the author, during presentation of the author's work at general meetings in both institutions. The participants were thus not selected from a pool of participants already registered with the University of Leeds or Sheffield. To the author's best knowledge, no participant had any experience with focus groups.

4.1.2 Method

Each focus group session lasted approximately one hour and was oriented around the following themes: cooking habits and activities, tool design, cooking, tool use, kitchen environment, and age effect. These themes were selected because they cover older people's handling and life in their kitchen, and tools suitability to the population of interest. These themes were addressed with the questions listed in Figure 4.1. The questions were developed to ask people about the significance that cooking has in their life, difficulties they can encounter whilst cooking, but also what sort of utensils they use. Additionally, the questions had to bring people to confess how age affected them in any of these domains. Care was taken to produce short and precise questions to avoid confusing or influencing people.

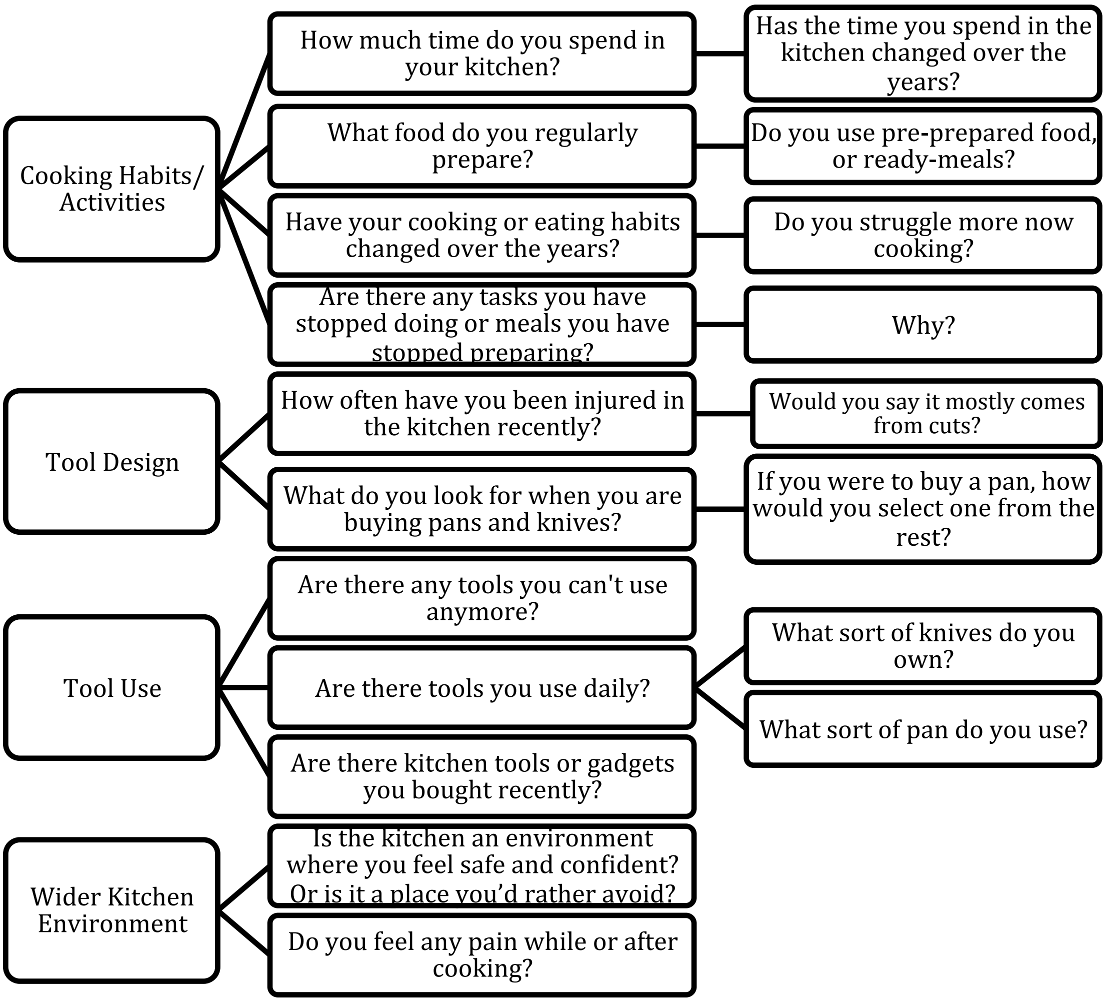


Figure 4.1 List of questions asked during focus group sessions ordered by discussion themes.

The focus group was based on a semi-structured approach, where researchers only asked questions to keep the discussion live when it was dwindling and to make sure all the themes were tackled. The priority was to let people talk, react, interact with each other, comment on each other's opinions, and control the direction of the discussion. Researchers made sure all the participants participated and answered the important questions. The purpose of the questions was to get people talking, to have them share their experiences with the group and get the discussion going. The researchers present tried to have as little participation in the discussion as possible, so as not to influence the participants and thus avoiding the main risk of focus groups: putting the words the researchers want to hear in the participants' mouth. The questions were ordered as seen in Figure 4.1, yet topics generally flowed from one to the other during the discussion.

The sessions were divided in two for the older people. During the first part, people were invited to sit around a table for the focus group as explained above. In the second part, they individually performed a few tasks and series of tests, which are detailed in further sections. As the overall session for older people was long (around two hours) a 15 minutes break was offered at half time. Tea, biscuit and coffee were offered all along the session making the participants more comfortable and at ease. Every focus group session was video recorded. The author analysed the session by transcribing every word pronounced during each session and looked for keywords and recurrent words, sentences, and expressions within each session and between all of them.

4.1.3 Results

When asked why they decided to participate people said they were fed up with faulty packaging and utensils design. To a large majority they admitted that they struggle opening "things" (four groups out of five) and that pans were "getting heavier" (five groups out of five). This already indicated an apparent problem due to ageing.

The discussion started on the subject of how older people cook and what they cook. Most of the participants cook from scratch, which implies preparation, and therefore utensils handling and time spent in a kitchen. The time spent in the kitchen fluctuates a lot from one person to the next, but also with the day of the week. People tend to spend more time in the kitchen at weekends and when they have guests over. Nevertheless all the participants seemed to have a common daily routine when it comes to meal. They generally have a short breakfast and lunch with respectively porridge and sandwiches, and would cook for a large meal for dinner. Most people estimated that they generally spend 15 minutes in the kitchen for breakfast, 30 minutes for lunch and one hour for the evening meal. This led to a majority of people spending a good two hours per day in their kitchen cooking and washing up. It must not be forgotten that those durations are averages over all the participants, and that seven participants out of 17 admitted spending one hour or less a day in their kitchen. It is important to point out that those differences did not come from disabilities but rather from habits (e.g., some people do not like to cook), family situation (e.g., living alone or with a partner), and diet (e.g., being vegetarian or having a medicine restrictive diet). However regardless of cooking habits all participants stated that they usually cook in bulk and freeze prepared food for another day, reducing the cooking time for that day.

Early in the session people were asked to describe the most frequent meal they cook, and this rapidly led them to tell the research team that utensils namely pressure cooker and pans were "heavier than [they] used to be". This observation was not from the actual weight of the utensils, but rather more from the evolution of the perceived weight of older participants' own pans. Which led to the first main research interest: have their cooking habits changed over the years? As expected many changes had occurred with time. Of course participants admitted that they get tired more easily especially "when [they] have people around and [they] have to do proper cooking" and "that didn't use to be the case". They find things a bit harder to grip: "I don't think I've got the wrist and thumb. I can't grip as well as I used to. Twenty years ago I […] would have peeled swede and think nothing of it." They also find that "cutting and chopping is getting more difficult, […] not that the meat is getting tougher". Early in the session, participants already commented on the fact that age has had an effect on their perception and use of kitchen utensils.

Moving further into the discussion on cooking habits and food cooked, age was not the only factor influencing change over the years. The food older people eat and the way they cook it have evolved with the evolution of technology and society. The world keeps on changing, people's lives change with it, thus the time spent in the kitchen as well as the food prepared and eaten have changed. Firstly, when the older subjects were younger kitchens were different. People used to have giant chest freezers, and aluminium pans, and used to overcook food. Today we know that aluminium pans "are not good for you", and aliments loose their nutriments if overcooked. "Nowadays we are much more aware, […] everything is also quicker and healthier, more balanced diet". Furthermore there is nowadays a greater concern about environment and recycling, and that is true for all generations. Participants were heard saying: "small pans aren't safe, so sometimes I'm wondering: should I use a big pan but I'm wasting water". Therefore older people follow, as well as the rest of us, the actual trend on environmental respect and preservation. Finally they all had their little preferences, for instance some were vegetarians, some cooked from scratch, and some tried to be seasonal. As expected older people are not just one group, they are all different from one another and have a wide variety of habits and styles.

Secondly, the most important reason for change was the change of lifestyle. In our society as time goes by children leave the parental house and after a certain age people stop working and retire. Those major life changes have undoubtedly a great effect on one's lifestyle. Therefore older people find themselves with more time and less mouths to feed, which inevitably changes one's cooking habits, "I spend half as long in the kitchen as I used to when the children were around". A widowed person living alone does not live the same life as they did 30 years ago when they had a job, a partner and children for instance. Interestingly although for most people this is how their life has evolved, they did not all adapt their cooking habits in the same way. For example while some spent a lot of time cooking when they had children and now only prepare quick meals, others because they had less time due to their working hours mostly microwaved ready-meals and now enjoy preparing quality meals.

Further down the line of the discussion, in every group, people came to talk about the last factor to dictate their cooking habits, the one briefly mentioned at the beginning of the discussion: age. Firstly, age has generated evident effects on them and their habits with illnesses: "I had three months when I had cancer, and I had to eat 90% raw, and I actually felt fitter and healthier than any other time in my life", or impairments: "I've developed a back problem [...] I can't stand as much as I used to", or "I have an intolerance to sweet". Secondly, age also has a gradual effect subtler and more discrete, which is perceived when one observes what they could do in the past but cannot today. For instance participants reported that "some tasks are getting harder as you get older", or that what "used to be a one-person job" has become a two-person job ("I used to do it with one hand before"). Because some tasks have become more arduous and require more attention, or because older people get tired more quickly, they have with time developed some adaptations to cope with what has become everyday struggles. An evident adaptation is simply that they tend to sit down more to do things. They also use equipment to facilitate handling or reach such as "kitchen steps". The adaptations they rely on every day are even part of their daily habits, and they even tend to forget that such and such are adaptations that they are now using: "you make me think of all the adaptations I take for granted now". Nevertheless their adaptations cannot overcome all age effects and "by the time you are our age you've learned to avoid things".

Participants admitted with no shame that time has had an effect on the way they cook. However it is not all down to ageing and diminished abilities. Older people's cooking habits have apparently been mostly affected by society, technology or significant lifestyle changes. In the UK, appliances that were rare 30 years ago are now common such as fridges, dishwashers, microwaves or blenders. The development of such technologies and of their accessibility has changed older people's cooking habits but also everybody else's. Secondly, retail stores offer now a larger range of products; one participant believed that this broadening has been especially remarkable in dairy products, while another mentioned exotic products (e.g., fruits or foreign food). With more products also came more knowledge on nutrition aiding the whole population in eating better, healthier. Lastly, a person does not have the same life at 70 than they had at 30; they no longer have children to look after, or a job to go to, they have new activities and manage their time differently, which reflects on their cooking habits.

Nevertheless body-ageing effect is perceptible, sometimes it appears suddenly or is evident, and sometimes it grows subtly. Participants had apparently often found an adaptation to overcome a problem, but difficulties persist. In summary, cooking habits evolve with lifestyle changes through the course of life, and with the evolution of society, which brings new accessible technologies, knowledge, and products. In addition to that it is difficult to cluster out the part of ageing in terms of decreased bodily functions, disabilities, or illnesses on the evolution of cooking habits because it generally has a slow and gradual effect. Decreased capacities can become noticeable over a period of ten years for instance, and yet society and lifestyles also noticeably change over such a period of time. Therefore habits can change because of different things, not necessarily solely ageing. And where it is due to ageing, it generally causes such a slow effect that people do not necessarily notice it, or they develop adaptations without even realising they do. People observe the effects of ageing when comparing their actual performances on simple tasks such as lifting a pan, or opening a jar, to what they could do decades ago. Furthermore, it is hard to identify whether adaptations are a result of experience or physical ability constraints, because with practice people learn and improve techniques, and by definition older people have experienced cooking for longer.

Research and reports from the Royal Society for the Prevention of Accidents (RoSPA, 2002) suggest that a large number of 65+ (i.e., persons 65 years old and over) get admitted in hospital due to cuts to arms and hands by kitchen tool, many of which are related to knives. This number is suspected (Graham & Firth, 1992) to be significantly larger as (1/18 is reported) the majority of those injured in this age bracket are never admitted to accident and emergency. Yet when asked older people answered that they do not feel that more accidents are happening to them. To verify that, participants were asked where they believed they struggle most while cooking. The struggles mentioned were first due to the weight of pans, then it was the difficulty with opening packaging and reading labels, and finally the fact that they tend to be more careful in everything they do. Researchers had to stress on the history of accidents they had so participants would reveal that the most common incidents are the oven burns (e.g., “Burns from taking stuff out the oven”, “the worst thing is burns”) and knife cuts (e.g., “I’ve cut my thumb using a freezer knife”, “For me it would be knife”). They admitted that a significant difference in their behaviour was that they are more careful: “I haven’t dropped things because I’m aware that I’ve got to be careful”, “I am much more careful than I used to be about clearing it up to make sure I don’t slip”, and “you have to be a bit more careful when taking things out of the oven”. That self-consciousness is for some coming from the fear of accidents, possibly being more likely to happen at their age or with more gravity: “I’ve burned myself more as I got older”. However many disagree and one said for instance: “I’ve burned myself less, because I’m not in a rush. I haven’t got pressure”. The general feeling seemed to be that they “don’t think [that it is] worse than it used to be”, and that accidents happen rarely: “I can’t remember the last time, it was a long time ago”. For those who fear accidents more than they used to, they admitted that they “have to be a bit more careful when taking things out of the oven [and] are a bit slower at doing things”.

On the subject of accidents and safety participants came to declare that scissors were used as a replacement tool for knives, because they are safer. This therefore led the researchers to ask whether they used special tools or had found adaptations to replace tools a young adult might use. From the answers gathered there were two different kinds of kitchen implements: the hand-held objects such as pans, and the cooking appliances such as ovens. Pans, knives, peelers, and graters are the kitchen utensils most widely used according to the participants. From people’s comments, many seemed to own a set of pans and knives for cooking; they always end up using the same set of knives, composed of no more than three knives. They do not use a wide range of tools, there is often the favourite knife sometimes considered as “a very good friend”, proof of a certain affection towards favourite utensils. They do not really use kitchen gadgets, except maybe for open ring pull cans but they all complained about them. They would only use technology if it were “easy to understand, [and with] not too many programmes”. Technology use was mostly found on cooking appliances such as microwaves. “Microwaves get used quite a lot. That’s something that has changed quite a lot”. Most of the participants “use the microwave a lot because [they] don’t put the oven on anymore because of economy”. Even for some “now what has replaced the pressure cooker and the pan of boiling water is the microwave”. Nevertheless opinions varied, as other would say that they “don’t use the microwave much now” while they did before because they “used to rush home from work” and quickly throw something in the microwave, while now they “use the pan and the oven more than [they] used to”.

Whether it is about time spent in the kitchen or use of technology, habits and opinions differ widely from one individual to the next. Unsurprisingly it is the same thing for knives: some people use big knives, others like small ones, namely “kitchen devils”. However when asked to explain why they use a small or large knife it was not only down to individual preferences but also individual abilities. One person declared that she “used to use a chef knife but cannot grip around that [anymore]. It’s falling out of my hand because [she] can’t grip properly now”. Another said that she could grip small knives because they fit into her hand, while a third one admitted that as she got older her knives got smaller, they are easier to deal with as she has more control over them.

Older people are consumers and sometimes they buy new utensils or kitchen gadgets, or get rid of old tools they do not use anymore: “I got rid of my pressure cooker, I thought it was dangerous”. Pressure cookers are a good example because many believe they are “terrifying things”, because of past experiences: “I can remember once it was spurting, the thing spurted off the top”, “I got rid of the pressure cooker, my mother used it, it exploded...” Furthermore, older people seem to be rather critical towards utensils or kitchen gadgets. They were therefore asked about what they look for when they buy a product such as a pan. When asked how they select a pan in a shop older people had a lot to say and with an expert judgement. Combining all the answers, the characteristics on which a pan is evaluated by older people are: its weight, balance, price, brand, design, colour, quality, material, resistance, handle comfort, size, heat conductivity, and online customer reviews. Oppositely, it was found by the author through a quick investigation on web stores that pan makers advertise their products online with the following characteristics: non-stick, hot spot, durability, heat distribution, scratches protection, and dishwasher safe. Participants seemed to precisely know what they wanted unlike the tools designers.

No matter all those influential factors, selecting a new product appears to be, most of the time, attributable to a balance between price and quality. Participants said that they would not buy a set of pans but rather a single one that they really needed. They "at this age […] would definitely go for quality" over price, because they admit that they do not buy pan "that often". Their philosophy seems to be along the line that "as you get older you think never mind the price, look at quality", and then "you buy the best you can that is going to suit you best and feel good". This discussion also reflected that it is important for them to weigh the pan and to feel it before buying. Therefore the pan has to be of good quality, but it is important for it to be comfortable and light. Unfortunately often those two characteristics do not go together, for instance "Cast iron pans are heavy but cook well", while food gets burned in light ones. Participants believed that "there's got to be a balance somewhere between a pan that cooks well and one you can actually pick up". Here again the example of pans highlights how their product selection process has changed with time, how they had to "stop using heavy pans, [and start using] smaller ones, lighter". They also can now buy smaller pans, as they do not cook for a big family anymore.

Participants expressed their feeling that designers "need to put more thought in the design of handle". Not having any engineering or designer background they nevertheless were keen on giving helpful advices or ideas on how to improve currently available products: "when it's something you need to grip hard it has to be smooth", or "rubber would be good, good for gripping". First they detailed the material properties of pans: "heavy base aluminium has gone out [and] copper base are really expensive [while] metallic handle conduct heat", and "non-stick coated pans [should] only [be used] for milk and omelette, because it comes off. Teflon is rubbish, you want anodised ones". Secondly the size of the pan is evidently very important. If it is too small then "flames comes up" the side, and it "tips up and burn you", "they're dangerous". Finally they concluded by saying that "old age doesn't come easy", and that they "are being more careful and use more often two hands" because an action such as "lift and turn when pouring is difficult" because "the pan can be too heavy."

The researchers noticed that in every session the brand Le Creuset was recurrent because their products "cook well". Yet because those pans are "cast iron" and therefore "bulky" and "heavy", people had to "change for stainless steel [because they] are easier to lift out". This is a perfect example of the dilemma older people have, and how they adapt or opt for different designs that suit them better. It is something all the participants agreed on: as you get older things get heavier. They have to change their pans for lighter ones, or if they want to keep a good quality of cooking get one with two handles. "Two handles pans [are] easy to pick up and put down, [I] haven't bought any new ones without two handles. [It is] a lot safer to use two handles [pans]." Finally the ultimate test when selecting a new pan in a shop is the handling, the pan has to feel good in the hand and ensure a good grip. There is a gap in product range. None of the participants have found a light, comfortable pan that they can use with a single hand and that gives good quality cooking.

Finally the discussion moved on to mobility shops. They all agreed that there are some good products with good design in such shops. However they all wondered: "why should it be labelled as special, when if everyone used it, it would be normal? And if it was in mainstream, high street shops, it wouldn't be special." They all agreed that there is a negative connotation with mobility shop products, and to fight that those products should be present everywhere because they are good for everyone. They avoid mobility shops because they said that they are "depressing", "awful", and "make people feel even worse". Good and adapted products are sought and in high demands by older people. However in the few cases where a good product exists and is attractive the distribution of such product is not. The problem appears not to rest solely in the design of the product but also in its distribution and integration in our everyday life.

To conclude the discussion a pan, designed for experimental purposes, was presented to evoke debate, and collect reactions to a specific tool. This pan was a wok bought in a public hardware store, from which the handle was replaced by a cylindrical hard Nylon handle with a 60 mm diameter (Figure 4.2). Such handle diameter size for a pan, to be used in the following activities, is out of norm. First people had a look at the product and thought it would be too big to be comfortable, and observed that it was the sort of pans that are found in mobility shops for people with arthritis. Then, they had a go at it, and picked it up. While some of them remained on their first impression, a majority were surprised by how comfortable it felt. They argued that one might have to get used to it, but by having more hand in contact with the handle they felt they had more control over it. This final point showed once more the difference between people but also the strength of preconceived ideas when it comes to produce judgement.

Figure 4.2 Kitchen wok with a 60 mm diameter hard plastic handle. This pan was used at the end of the focus group sessions, for the high-speed video recordings, the rice-pouring task, and for Chapter 7's experiments.

In the end it appears, according to older people themselves, that they do not struggle so much in their kitchen. Older people have changed their ways of cooking but more because of lifestyle, society and technology evolution rather than age related disabilities. Nevertheless older people would summarise ageing as follows: with age you have less grip and you have to be more careful, which makes one do things more slowly: "I think I am more conscious… careful". They admit that you are "not as capable as you get older but you think more" and "you make allowances" because "you know you have to be more careful". So even if age does not bring dramatic impairments, it can, in certain situations, be a handicap, yet people have found adaptations to solve resulting problems, such as preparing food sat down instead of stood up. They have also bought new products with design fitted to their abilities and needs. They do not see age-related physical abilities diminution as a handicap; they simply do things more slowly and more cautiously. However they see danger in the kitchen when one starts to lose mental ability, such as memory or attention. Independence in the kitchen does not come to an end because of diminishing physical abilities but rather from loss of mental ones. Nevertheless they agreed that with time they were forced to look for more fitted kitchen tools because they struggle more than they used to. Unfortunately, they could not find attractive adequate designs and mobility shops repulse them. Therefore even if according to them, physical abilities are in a majority of cases not a factor leading to independent living, life can be made easier, simpler and more enjoyable with adequately designed tools.

In the following stage of the research anthropometric measurements and dexterity task performance measures were collected to observe the differences between young and older adults in hand dexterity and its effect on performance. The older participants took part in a focus group session of one hour and in an activity session of another hour consecutively. Young participants were recruited for a single session to compare older people's performances for the activities.

4.2 High-Speed Camera

4.2.1 Subjects

Of all the 14 older participants who came to Leeds one had to leave at the end of the focus group, which resulted in only 13 participating in the handling activities in Leeds. Sheffield organised two sessions with three participants each. The second session was run independently from Leeds and therefore only included a focus group leading to the collection of activity readings for only three out of the six participants from Sheffield. As a consequence out of the 20 older participants who took part in focus group sessions, only 16 performed the handling activities. There were therefore 16 older adults (age mean 69.64 years, age range 61 to 84 years; two reported left hand preference, three males) who took part in the high-speed video (HSV) recordings.

Young participants were invited on an individual basis, as they did not have to take part in a group discussion prior to their tests. Of all the older participants invited a total of 16 took part in the activity session, thus 16 young participants were recruited in Leeds (age mean 26.25 years, age range 20 to 38 years; one reported left hand preference, three men). The young participants' sessions were not organised in conjunction with Sheffield. Therefore the young participants only underwent tests in Leeds. Each session lasted approximately 30 minutes. All participants had normal or corrected-to-normal vision and no history of neurological deficit. All participants provided informed consent prior to inclusion in the study. The study was approved by the university ethics committee.

4.2.2 Method

For this first test, participants were standing in front a counter-height table (height 90cm). The participants were asked to position the pan in front of them as if they were cooking with it. Leaving participants free to orientate the pan handle as they pleased made sure the pan was placed in a comfortable position for each participant before the task. Once the pan was in place, the participants were asked to reach for the handle and slightly lift up the pan off the table. A high-speed video camera pointing at the pan handle recorded the movement of the hand and fingers grasping the handle (see Figure 4.3).

Figure 4.3 Drawing of the high-speed video recordings setup, where a reach-to-grasp movement was filmed with a high-speed camera when reaching for a power grasp around a pan handle.

The researcher signalled the participants when to reach for the pan, the movement was repeated twice. The pan used in this experiment was a wok bought in a well-established hardware store. However, the original handle had been replaced by a new handle, designed by the research team to be tested in this experiment and following ones. The specifically designed handle was a hard plastic cylindrical handle with a diameter of 60 mm, and a length of 100 mm. The pan and handle together weighted 883 g. Such design had been chosen to fit requirements of other experiments but also because literature showed that a 60 mm diameter seems to be in the zone of the diameter where a human power grasp is at its strongest (Petrofsky et al., 1980), even if it is greatly depended on people's grip span.

The HSV Camera was set with a resolution of 800x600 at a sample rate of 1000 pps. The HSV recordings show the exact movement of hands coming in contact with the pan handle, gripping it and lifting it up. The camera rested on a table at the same level of the pan and was facing to the right-hand side of the handle. Because the majority of participants were right-handed, filming the right side of the handle resulted in clear recordings of people's hand wrapping around the handle. Two left-handed people took part in the study resulting in recordings from the opposite direction.

The purpose of this activity was to observe in detail how people approach a pan they want to lift. This pan and similar ones were to be used in further experiments, where people would have to reach-and-grasp them (see Chapter 7). In order to fit those experiments to real life handling situations, observations of hand trajectory and grasp on pan handles were necessary. The setup of these experiments was to be based on people's natural grasp approach. Using a HSV camera permitted the observation of the orientation of the hand as it approaches the handle, the angles and rotations of the wrist during reach and grasp, the placement of hand palm and fingers, and the adjustments of position once contact had been made.

4.2.3 Results

Through the HSV recordings, many differences and similarities in people's way of grasping a pan handle were observed. People were left to orient the pan so that the handle was pointing in a direction that made the pan comfortable for them to pick up. They were left all liberty to approach and grasp the pans the way that best pleased them. Firstly, people extended their arm towards the pan. As they got closer, they increased their hand aperture. When their hand was close to the handle they slowly started to reduce their grasp aperture. This reduction accelerated as soon as contact was made. It was noticed that for all of the cases the aperture of the maximum grasp aperture was significantly wider than the handle diameter. The first part of the hand getting in contact with the pan was the hypothenar eminence or midpalmar space. Once the proximal phalanges were in contact with the handle, and before the middle ones touched the latter, location adjustments were made: slight displacements of the palm along the handle axis and orientation of the fingers. Next the fingers and the thumb enclosed progressively the handle at a similar pace before securing the grip. The application of forces and moments for lifting the pan is noticeable by even more palm and fingers placement adjustments.

Of all the 32 participants two used their left hand (one older adult, and one young adult), this resulted in 30 observations of right hand grasp and two of left hand grasp (**Appendix 1**). Evidently the great majority of people approached their hand from the right, as they are right-handed. The hand was placed on the side of the handle with the thumb on top of the pan or even on the opposite side (in opposition to the rest of the fingers), while the four remaining fingers were placed underneath the handle one along the other. The hand was in line with the forearm, as much as the angle of the handle permitted.

For most of the participants, young and older, the shape of the grip was very similar, the main difference between all the grips was the location of the hand relative to the handle. The differences in hand position mostly consist in differences in placement of the thenar space on the handle (i.e., space between thumb and index finger). It was noticed that the thenar space was more often placed above the handle rather than beneath it. Because the diameter of the handle was large, the researcher had been expecting otherwise: participants grasping the handle from underneath in order to present a larger opposing force to gravity. Nevertheless people with tiny hands were more tempted to place their hand underneath the handle.

The next activity was a series of anthropometric measurements, to estimate possible differences in hand size and dexterity between generations.

4.3 Hand Size and Wrist Range of Motion

4.3.1 Subjects

The subjects who took part in this activity were exactly the same as the ones who took part in the HSV activity. There were a group of 16 people above 60 years old and a group of 16 people between 20 and 40 years old.

4.3.2 Method

Hand sizes and Wrist Range of Motion (WROM) were gathered here. Measuring hand lengths and wrist angles with a measuring tape and a goniometer is long and laborious. Therefore instead of carrying out all the measurements on the participants, photos of people’s dominant hand were taken flat and straight on a measuring board for the hand size measure, and in the orientations shown in Figure 4.4 for the WROM. This reduced the length of the experiment for the participants considerably. Those photos permitted the researcher to measure the angles of flexion and extension of the wrist in different orientations (i.e., up, down, right, left). The participants were asked to bend their wrist as much as possible within the limits of comfort. The hand size was measured from the styloid of the wrist to the tip of the middle finger.

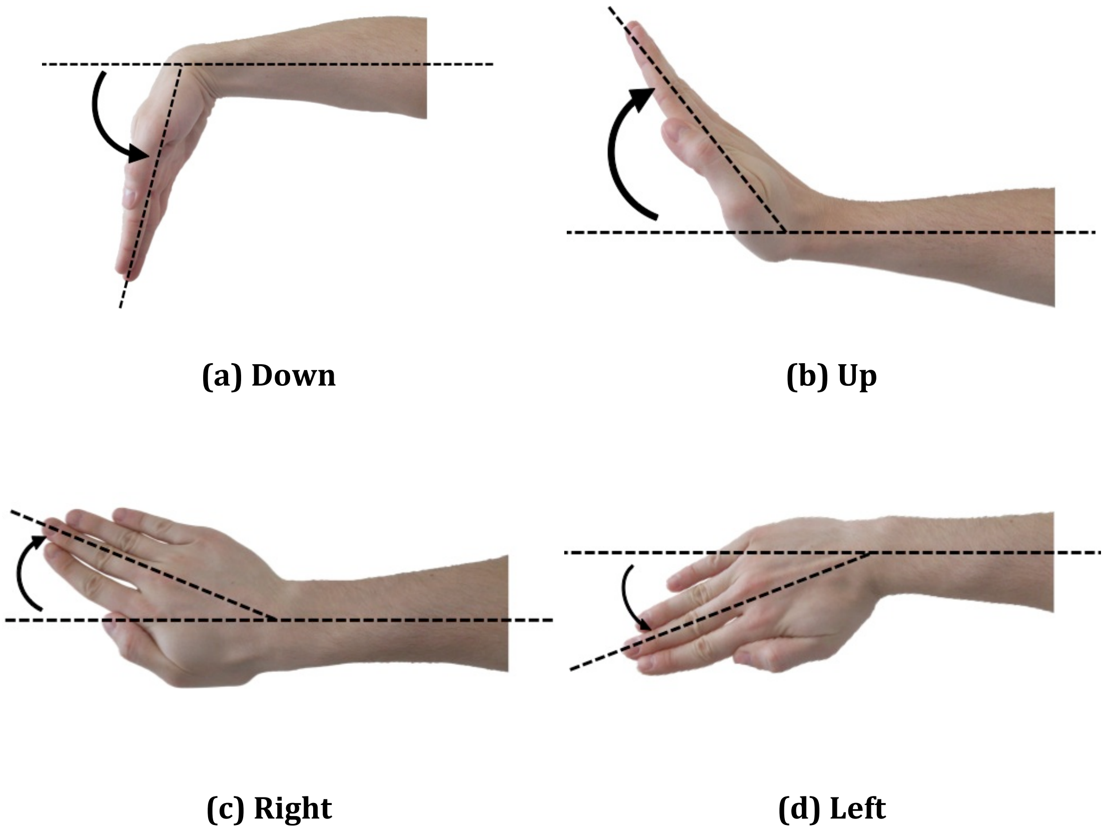


Figure 4.4 Orientation angles of participant's wrist flexion and extension. The angle of flexion and extension is measured between the axes of the forearm and of the third metacarpal of the hand in line with the middle finger. The measurements were made for the following flexion (a) downward, (b) upward, (c) right, and (d) left.

The purpose of taking such measures was first to have a referential database of hand sizes and WROM. Secondly it allowed anthropometric comparison between gender and age groups. The author was expecting hand sizes to be larger for male but not to differ with age. On the other hand WROM was expected not to differ between genders, but to decrease with age. This is one more step towards knowing the targeted population (i.e., older people) and a way to verify through a small population sample how dexterity in the wrist can be affected by age.

4.3.3 Results

Wrist Range of Motion

The first anthropometric measure of interest was the WROM, and how it differs with wrist angle and age. WROM is defined as the maximal angle to which a person can bend their wrist in a specific direction. Participants had to bend their wrist into four different positions: Right, Left, Up, and Down. Those positions corresponded respectively to the following (see Figure 4.4):

- Right: an ulnar deviation bending the wrist so that the little finger nears ulna bone,
- Left: a radial deviation bending the wrist so that the thumb nears the radius bone,
- Up: An extension bending the wrist so that the dorsal aspect of the hand nears the lower arm,
- Down: a flexion bending the wrist so that the palm nears the lower arm.

A repeated measures (or mixed ANOVA) analysis was run in order to identify whether the WROM were dependent of the direction the wrist was bent towards. The Mauchly's test being significant, sphericity could not be assumed, a Greenhouse-Geisser correction (ε) was therefore applied to the degrees of freedom. Partial eta squared (η^2) values are reported for statistically significant findings. Eta squared is the proportion of total variability in the dependent variable that is accounted for by variation in independent variable. It is the most commonly reported estimate of effect size for ANOVA (Levine & Hullett, 2002). Reporting the effect size for statically significant findings shows how much variance in the dependent variable is a result of the independent one. The effect size is considered as large once larger than 0.138 (Cohen, 1988), then there is a strong relationship between the variables.

The variability of the reported measurements is graphically represented as error bars in this chapter. They are a representation of the standard error of the mean (SEM), which is calculated with the sample standard deviation divided by the square root of the sample size. The direction in which the wrist was bent had a significant influence on the angle of flexion or extension ($F(3,90) = 283.734$, $p < 0.01$, $\eta^2 = 0.904$, $\varepsilon = 0.846$). Participants of all ages had more dexterity in vertical flexion and extension (i.e., Up and Down) than horizontal ones (i.e., Right and Left). In both age groups the WROM was small for Left flexion, slightly bigger for Right, then drastically bigger for Up, but the highest values were reached in a Down flexion.

The main objective of the analysis of this task was to determine whether there were differences between the two age cohorts, between young and older adults. To compare the results of the two age groups a MANOVA (multiple ANOVA) analysis was used. MANOVA groups individual One-way ANOVA analyses, and shows whether any of the independent variables has an effect on the dependent variables. In the current case the direction of WROM were the dependent variables and age the independent one. There was a significant effect of age on participants' dexterity in the Right direction ($F(1, 30) = 7.754$, $p < 0.01$, $\eta^2 = 0.206$), the Left direction ($F(1, 30) = 5.275$, $p < 0.05$, $\eta^2 = 0.150$), the Up direction ($F(1, 30) = 11.673$, $p < 0.01$, $\eta^2 = 0.280$) and the Down direction ($F(1, 30) = 7.175$, $p < 0.05$, $\eta^2 = 0.193$). This means that age had a significant effect on wrist range of motion or flexibility in all the directions. Older participants were significantly less dextrous in all directions except in a left flexion, where they were significantly more dextrous than young subjects. Figure 4.5 reveals the mean angles older and young subjects could reach in all directions.

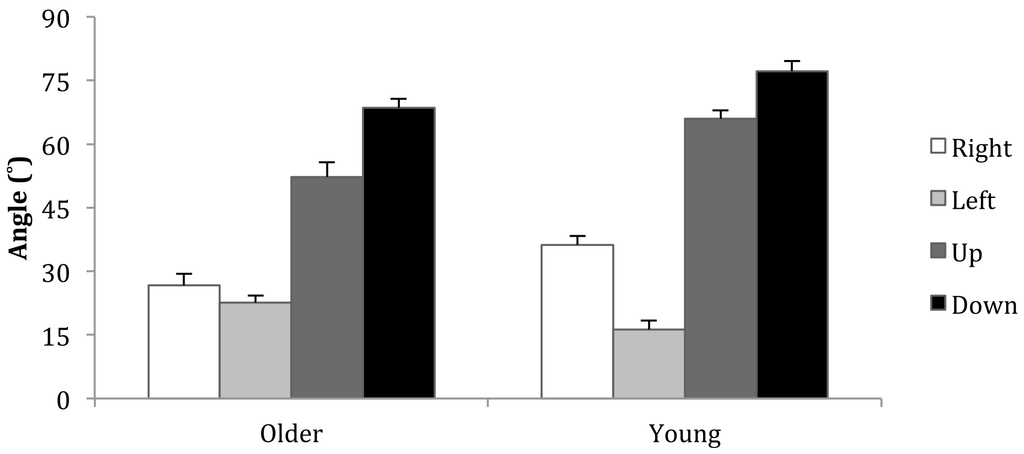


Figure 4.5 Average angles reached and variances of the wrist range of motions for every direction in each one of the two age cohorts.

Hand Size

The following measurement was on hand size. The hand size was measured from the tip of the middle finger to the wrist crease. A one-way ANOVA showed that there were no significant differences in hand size between older and younger people ($F(1,28) = 0.009$, $p = 0.927$). A Pearson correlation coefficient was computed to assess the relationship between people's hand size and wrist range of motion in all studied directions. There were no significant correlation between participants' hand size and wrist range of motion in any direction of flexion or extension.

However there was a positive correlation between the angles reached in Up and Down directions ($r = 0.377$, $n = 32$, $p < 0.05$). Increases in one of the vertical range of motion were correlated with increases in the other one. There was also a strong, positive correlation between the angles reached in Right and Up directions ($r = 0.553$, $n = 32$, $p < 0.01$). Increases in the range of motion to the Right were correlated with increases in the Up ones. As expected the flexion in vertical direction was positively linked with the extension in the opposite direction. However this was thought to be the case as well in the horizontal direction.

The last task required subjects to pour rice into a container and observe how performances differ between age groups.

4.4 Rice-Pouring

4.4.1 Subjects

The same participants who took part in the two previous activities took part in this last one, except for the five older persons who were invited to the last session in Leeds. Indeed for this last session, organised in Leeds, no researcher from Sheffield University could come and therefore equipment and personnel were missing to run the full batch of tests. This resulted in only 11 rice-pouring task measurements for the older people. All the tests could be run with the young participants, resulting in 16 rice-pouring task measurements for that age cohort.

4.4.2 Method

The final test of the University of Leeds was a broad imitation of a common task to be performed, if not daily, very frequently in an average British kitchen: pouring a product from a pan into another receptacle, in the present case dry uncooked rice. Dry uncooked rice was chosen because it is a food to which subjects were familiar, and keeping it dry and uncooked helped in its conservation, manipulation, and consistency in weight and volume across sessions. Lastly, grains of rice are a small solid product that can be poured similarly to a liquid, and yet does not present the risk of slippage that liquids do, which were to be avoided for health and safety reasons. An identical pan to the one used for the HSV recording was filled with 200 g of rice. People were to pour the whole quantity of rice from the pan into a bowl. The task was demanding because the wok did not have any spout, and the bowl had a diameter significantly smaller than the wok. The quantity successfully poured into the bowl was measured, as well as the time taken from the moment people took hold of the pan to the moment the pan was emptied. This task was repeated three times by every participant.

Replicating a simple task that people are likely to perform on a daily basis while cooking permits the observations of possible daily living difficulties. The focus groups were designed to gather older people's feelings about their cooking, the HSV recordings were to show whether any differences in grasping techniques existed between generations, and the anthropometric measures were to reveal any dexterity variation with age. The rice-pouring test is the last element that brings all previously gathered data into one test. People have their own perception of their performance, and physical measurements can suggest behavioural hypothesis, but these do not necessarily correlate with people actual performances. By measuring people's time and success rate in a simple task is likely to unveil whether some are better than others. This last test is a simple way to see whether older people show evident struggle while preparing food. A multiple regression model was run in order to observe whether the WROM, in other words the dexterity, has an effect on people's performances (i.e., time and weight) during a simple cooking task (i.e., pouring food from a pan into another container).

4.4.3 Results

People were asked to only use one hand, their dominant hand, to pick up the pan and pour the rice. The distributions of duration of action and weight poured are plotted in Figure 4.6.

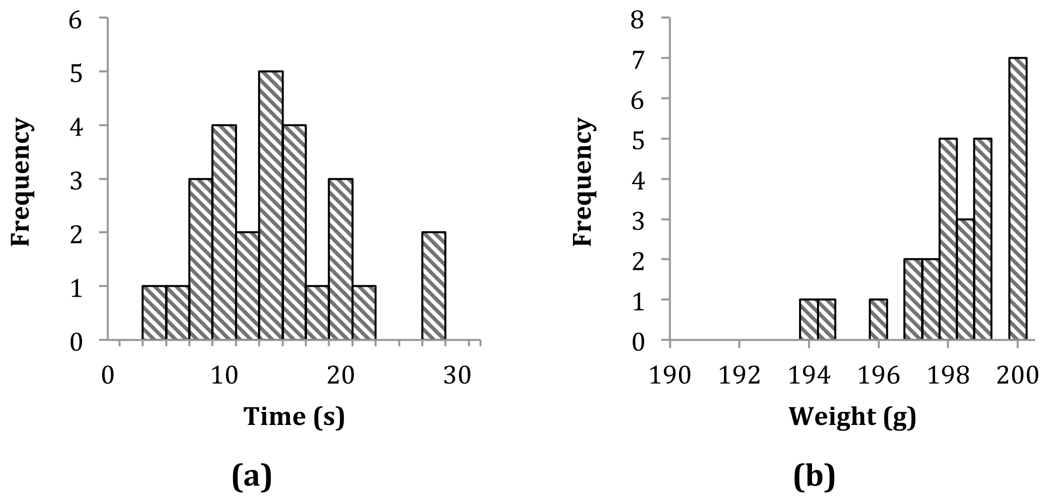


Figure 4.6 Distribution of (a) the duration of the pouring action and of (b) the weight of rice successfully poured into the bowl for every attempt.

Figure 4.6 and the Shapiro-Wilk test indicate that trial times were normally distributed ($p = 0.220$) while weights successfully poured in were not ($p < 0.05$). Therefore the time scores were compared with a t-test while the weight scores were compared with a non-parametric technique: Wilkinson Signed Rank Test. In the case of the normally distributed data, t-test was chosen over ANOVA because in ANOVA equal variance is assumed, while the t-test runs a Levene's test to verify the equality of variance, and details both cases. Plus the t-test gives a two-tailed result, useful in this case as it was not known whether participants were, on a given try, quicker or slower, or whether young adults were quicker than older people.

The times of the three trials for each participants were not significantly different from one another ($M_1 = 13.56$, $SD_1 = 6.46$; $M_2 = 13.25$, $SD_2 = 6.99$; $M_3 = 13.58$, $SD_3 = 7.46$) $t_{1\text{-}2}(27) = 0.331$, $p_{1\text{-}2} = 0.743$, $t_{2\text{-}3}(27) = -0.311$, $p_{2\text{-}3} = 0.758$, $t_{1\text{-}3} = -0.023$, $p_{1\text{-}3} = 0.982$). Even though participants were trying different approaches or techniques to be quicker or more accurate they were no significant differences in the times they took to achieve the task. There was an equality of variance for both age groups. There was no statistically significant difference in task duration between young ($M = 12.32$, $SD = 6.24$) and older adults ($M = 15.12$, $SD = 5.84$), $t(25) = 1.174$, $p = 0.251$, $n = 25$). These results suggest that age does not have an effect on the time people took to perform the pouring task.

A Wilkinson Signed Rank Test showed that the quantities successfully poured in the bowl were not significantly different from one another ($Z_{2\text{-}1} = -0.708$, $p_{2\text{-}1} = 0.479$, $Z_{3\text{-}1} = -1.139$, $p_{3\text{-}1} = 0.255$, $Z_{3\text{-}2} = -0.740$, $p_{3\text{-}2} = 0.459$). Similarly to the time scores, despite the fact that participants were trying different approaches or techniques to be quicker or more accurate they exhibited no significant differences in the quantity they could successfully pour in the bowl between each trial. However unlike the time scores there was a significant difference between the scores of older people and younger people ($Z = -2.499$, $p < 0.05$, $n = 25$). Nevertheless, one must not report statistical analysis blindly, looking at the raw data the range of grams of rice poured went from 193 g to 200 g for the young cohort with a mean of 198.75 g, whilst older people had a range from 191.8 g to 199 g with a mean of 197.27 g. The difference in range was less than ten grams, and there was a 1.5 g difference between the two means. The statistical analysis showed a statistically significant difference between the two age groups; nonetheless in real life situation such a weight difference is reliable but fairly trivial.

Finally, a regression analysis was run to detect whether WROM had an effect on people's performances in the rice-pouring task. A regression analysis consists in building a model on the data obtained to predict what a given value would result in. The independent values here were hand sizes and wrist angles in all directions, while the dependent value was first the time and then the weight poured in. A regression analysis results in coefficients corresponding to the following equation:

$$y = B_{constant} + B\,x \qquad \text{Equation 4-1}$$

Where y is the dependent value, and x the independent value. The regression analysis results in the unstandardized and standardized values of B and $B_{constant}$.

Table 4.2 Regression model coefficients for the time taken to transfer the entire quantity of rice.

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
1	(Constant)	48.982	25.771	
	Hand	-1.504	1.304	-.246
	Right	-.193	.182	-.350
	Left	-.029	.181	-.038
	Up	-.034	.124	-.072
	Down	.004	.170	.007

Table 4.3 Regression model coefficients for the quantity of rice successfully transferred.

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
1	(Constant)	199.574	7.182	
	Hand	-.216	.363	-.136
	Right	-.013	.051	-.089
	Left	-.039	.050	-.201
	Up	-.003	.035	-.025
	Down	.052	.047	.313

Table 4.3 and Table 4.2 show that for all the angles the B coefficient was extremely small, meaning that the wrist range of motion had no significant effect on the quantity of rice poured into the bowl or on the time taken to do so. The B coefficient for hand size was slightly larger but remained insignificant.

4.5 Discussion

Older people tend to enjoy cooking and spend time in their kitchen. The evolution of their cooking habits over the years is no pure results of ageing but also of the evolution of kitchen implements, people's mentality, society, and lifestyle. Nevertheless, no matter all the improvements technology has brought, when asked, participants said that cooking always comes down to basic tools such as knives and pans. With ageing, participants have noticed deterioration in hand force, and wrist and shoulder dexterity, which force them to find adaptations to overcome these losses and 'make do' with an inferior or unsuitable product, or with a technique that they have refined with time and practice. Nonetheless, there comes a point when the design of their kitchen utensils has become unusable for them, and participants noticed that it has been impossible for them to find an adequate pan, fulfilling all their requirements, which are not over fastidious. In the rare cases where a fitted design is on the market, it is solely advertised in mobility shops, and unfortunately those shops are unattractive places to go shopping in and are strongly linked in people's mind to disability. The lack of attractive, adapted and affordable products reflects that designers are disconnected from them.

The people who were willing to take part in this study are by default dynamic and enthusiastic, thus people who, for the most part, do not have major disabilities and are therefore not acutely struggling to cook. This might contribute to the observation that society, technology or significant lifestyle changes have had more effect on their cooking habits than age-related impairments. Nevertheless, they are the best representatives of global healthy ageing. They admit that they take more time to do things and are being more careful and paying more attention to what they do; leading to a slower pace. They are aware that every hazard is more dangerous for them; they are aware that they cannot react as fast; they are aware that they are physically more limited and have to make do. Older people affirm that utensils are harder to use, as you get older because of their flawed design. They pray for better-designed tools, even and especially for the simplest ones such as pans and knives, that would make their life easier. The purpose of these focus groups was thus to discuss product design with the end users in order to reconnect with them and know more about their lives and requirements.

The quantitative results obtained in the second part of the session brought great insight into the behaviour of people in relation to pan use, but also into the differences and similitudes between two distinct age groups. The study of people's reach-to-grasp-and-lift movement on a pan with high-speed cameras showed that the majority of the people tested had a similar approach across all ages. The hand was usually placed on the side of the handle, the dorsal aspect of the hand slightly facing upward. The study of participants' wrist range of motion revealed that wrist dexterity was highly dependent on the direction toward which the hand was directed regardless of the age. The results of this study confirm what previous research have established, and now appears as evident (Bland et al., 2008; Desrosiers et al., 1995b), older people seemed to be less dextrous than young. The large variance observed with older people for wrist flexion is likely to be the reason for the odd result of older people's greater dexterity in the left direction, due to the small size of the angles reached in that specific direction.

It can be hypothesised from the literature, the focus groups, and the quantitative data that older people have lower hand dexterity, physical abilities, and more difficulties in handling objects. Yet all of this does not explain how their handling performances are affected and by how much. The complementary study demonstrated that older adults might have lower dexterity, they do not seem to struggle more, or be less efficient in a simple cooking task than the young population. This does not correlate with what was to be expected, but it does correlate with how older people describe their abilities. According to them they are generally not less efficient, they are just more careful. It is hypothesised that the experience that older people have over younger people might play a major role in compensating for their lack of dexterity. The other hypothesis is that they are more familiar with such tasks than the young cohort, formed only of students who might not be a population keen on cooking. Additionally since the task was neither complicate nor physically demanding and lengthy, and performed in a lab environment with no risk and hazard, older people might not have been as cautious as they normally would, and therefore be as efficient as a young person.

This chapter described the first step of this thesis consisting in a study from which the main objective was to obtain some qualitative data on a population too often ignored in product design processes: the older population. The studies presented in the following chapters focus on the pre-contact and contact phases of reach-to-grasp movements, and on how low dexterity and age affect them. The following chapter describes an experiment done on the observation of pre-contact movement behaviour for a pinch grip.

Chapter 5

Pinch Grip Reach-to-Grasp in Older Adults

The shape and ergonomics of a product guides the way it is grasped and held, as well as the reaching motion of the hand. Product characteristics have a significant influence on reach-to-grasp motions' pre-contact phase. Previous research has demonstrated that older people's grip strength decreases with age, but little information exists on how age affects a reach-to-grasp motion. Following the work of Mon-Williams and Bingham (Mon-Williams & Bingham, 2011), Flatters et al (Flatters et al., 2012) demonstrated that the structure of one's reach-to-grasp was influenced by the object's friction, size and distance. Both studies used pinch grips because it forms the basis of any precision grip, is a straightforward system to represent, simulate, and study, and is favoured for small objects, where small forces and accuracy are required.

This chapter aims at investigating the structure of older people's reach-to-grasp movement. It is hypothesised that similarly to what Flatters et al. have found with young adults, older adults adapt their approach according to the object's properties. It is thought that older people exhibit more 'stop-and-go' movements than young adults in identical conditions. The study reported here describes how product characteristics affect the structure of older people's reach-to-grasp motion. Many product characteristics, such as temperature, friction, grip size, and weight are likely to affect reach-to-grasp because they have a significant effect on grip force (Carnahan et al., 2001; Westling &

Johansson, 1984). Object width and surface friction have been favoured by literature because they have some of the most significant influences on grasp stability (Edgren et al., 2004; Enders & Seo, 2011; Grant et al., 1992; Jenmalm et al., 2000). They are also paramount in accurate targeting and collision avoidance (Bootsma et al., 1994; Rosenbaum et al., 1999). Furthermore, the approach moment has already been shown to be dependent of those characteristics (Flatters et al., 2012; Mon-Williams & Bingham, 2011). Object width and surface friction are thus likely to be the most influential factors, and were thus selected to be the independent variables analysed in this chapter together with object distance from user. Object distance was added to the analysis based on the observation of previous research on reach-to-grasp showing its significant effect (Flatters et al., 2012; Mon-Williams & Bingham, 2011).

It is hypothesised that older people will be slower than young adults, but that they will open their digits wider to be sure not to bump into the object. This would correlate their claim, where in Chapter 4 they admitted being more careful than they used to be when handling and using handheld tools. Older people are also known to have lower hand dexterity than young adults. In order to investigate whether that impaired dexterity could be the reason for any difference in behaviour, a series of tests were run where young and healthy adults wore Cambridge Impairment Simulators Gloves (CISG). Because it is thought that low dexterity is the factor mostly dictating older people's reach-to-grasp, it is hypothesised that CISG would be an effective old age simulator in terms of hand grip.

This chapter thus reports the influence that objects size, surface friction, and location relative to the user have on people's reach-to-grasp movement. Through the analysis of the kinematics of reach-to-grasp motion, it uncovers the motion fluctuation with age and with loss of dexterity.

5.1 Methods

5.1.1 Participants

The research in this chapter was carried out with young people wearing CISG and older people. Having had access to Flatters' et al raw data (Flatters et al., 2012), the data obtained from those two population cohorts is compared to the one of Flatters' on free-handed young adults. Twelve unpaid older people (age mean 73.5 years, age range 62.0 – 84.0 years; nine females; 11 reported right hand preference) and twelve unpaid young people were recruited (age mean 25.3 years, age range 20.0 – 33.0 years; five females; 12 reported right hand preference). Flatters' cohort consisted of twelve unpaid participants (age mean 27.7 years, age range 20.5 – 47.1 years; seven females; 11 reported right hand preference). All participants had normal or corrected-to-normal vision and no history of neurological deficit or hand deficiency such as arthritis. Maximum pinch grip aperture was measured for each participant (older group: maximal grip aperture mean 14.6 cm, and range 13.1 – 16.5 cm; Flatters' young group: maximal grip aperture mean 15.8 cm, and range 13.0 – 21.0 cm; young group with gloves: maximal grip aperture mean 15.0 cm, and range 13 – 18 cm). All participants provided informed consent prior to inclusion in the study, which was approved by the University Ethics Committee. Participants were randomly selected from a list of contacts, and recruited by email or phone. They were completely naïve with regard to the present study's purpose.

5.1.2 Procedure

Participants were asked to reach-to-grasp-and-lift small stimuli. The stimuli were rounded end (25 mm radius) plastic (black Nylon) cylinders (25.4 mm diameter) resting along their length on wooden supports. The cylinders varied in length 5, 7, and 9 cm (narrow, medium, wide), so did respectively the supports, remaining always shorter than the cylinder (see Figure 5.1). For every cylinder length two different surface friction conditions were tested. Indeed the two curved ends of the cylinders, which participants had to press their digits against in order to pinch grip the stimuli and lift them, were covered with coarse-grade sandpaper (Aluminium Oxide, P50) or petroleum jelly (Vaseline®, Unilever). The jelly was applied with a soft-bristled brush to the grasp surfaces of the stimulus between trials of this condition (application was repeated on alternate trials). The application of such materials introduced two distinct coefficients of friction (high friction being dry, and low friction being covered with Vaseline) for each of the three cylinder lengths. Temperature is likely to affect the stickiness of the Vaseline, but the frequent applications and the time gap between every pinch kept the surface at room temperature across all tests.

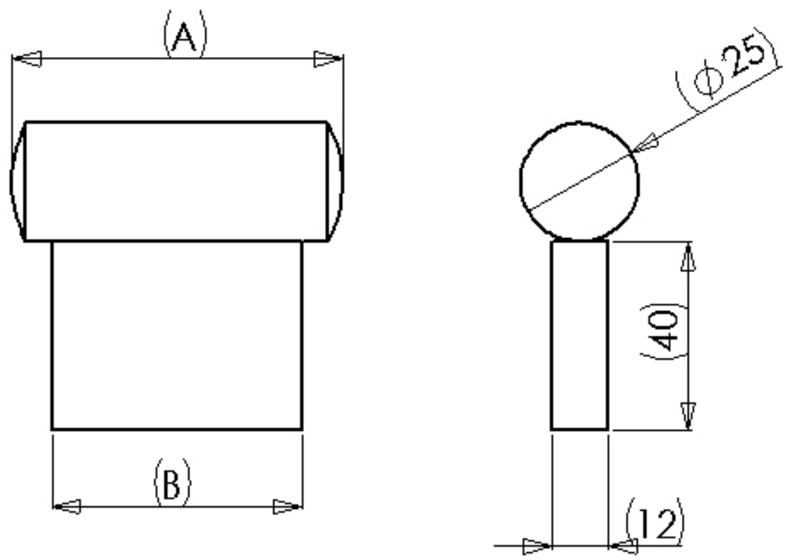


Figure 5.1 Object geometric properties. For each of the two friction conditions there were three objects with different grip width 'A' as discussed in the method section. 'B' is the width of the support base, which was scaled to the cylinders' length (33, 53 and 73 mm).

Participants sat in front of a table onto which the stimulus was placed. Infra Red Emitting Diodes (IREDs) were placed on the distal medial corner of the thumb and index finger, on the styloid process of the wrist and on the stimulus. Optotrak 3020 motion tracking system (Northern Digital, Ontario, Canada), consisting of infrared cameras pointing towards the table and a recording system, was used to record the location of those markers. Before every test participants had to place their hand on the start position, which consisted of a raised support positioned 100 mm from the edge of the study table in front the participant. Stimuli were always positioned in the alignment with the sagittal plane of the participant's dominant arm, and with the cylinder axis collinear to their frontal plane at 100, 300, and 500 mm beyond the start osition. The setup of the room with the Optotrak camera pointing at the participant re aching for a stimulus is represented in Figure 5.2.

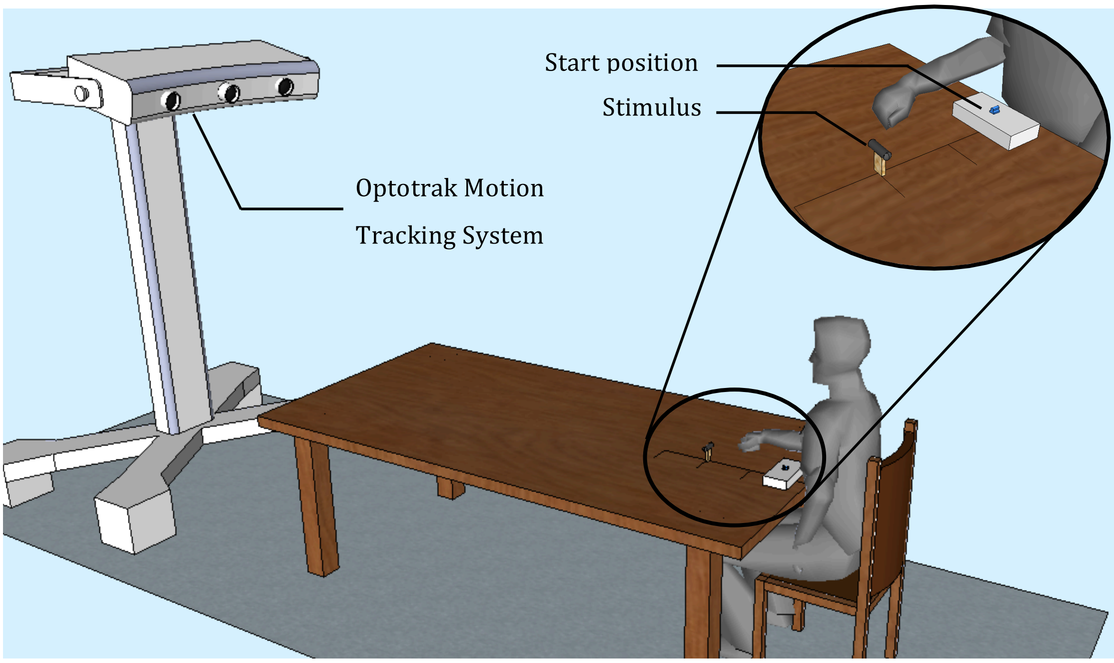


Figure 5.2 Diagram of the experimental set up of the reach-to-grasp experiment with Optotrak

For each stimulus combination (stimulus length, friction, and distance from table edge) ten successive reach-to-grasp-and-lift movements were repeated. There were a total of 18 conditions (i.e., 3 lengths x 3 distances x 2 frictions), hence 180 lifts. The presentation of stimuli was grouped by the surface's friction condition, randomly ordered from one participant to the next. Width and distance were randomly presented to the participants within friction groups. High and low friction trials could not be randomly alternated because jelly residue on fingers could have altered the coefficient of friction for the high friction stimuli. Each session lasted approximately 45 minutes. A test could be repeated if: stable and static grip of the stimuli could not be achieved in the allocated time, the stimulus was knocked over or not gripped on the instructed surfaces, or the object was dropped before accurate completion of the trial. All those cases are referred to as 'drop' tests and counted when occurred. In case of failure, attempts were repeated until 10 successful trials were recorded or after 15 trial failures for older and 10 for young with glove, whichever came first.

On the "Go" oral signal from the researcher, participants had to reach the object and pinch grip it between their thumb and index fingertips as quickly and accurately as possible. The object was to be grasped, slightly lifted off the table top, and held in place until given the instruction to put it back down and come back to the origin position. Data acquisition started prior to any movement of the hand, and lasted four seconds resulting in participants having to hold the object in the air for approximately 0.5 to 1 second.

5.1.3 Measures

The kinematic data obtained and analysed was deduced from the location of the IREDs acquired at 100 Hz. Optotrak infrared cameras recorded the x, y, z location of the IRED, continuously during each test. Through a Matlab processing program, the speed, onset and offset times of each IRED, as well as the distance between IREDs were calculated from Optotrak readings. All kinematic values analysed in this chapter were obtained from this set of data. The grip aperture was defined as the distance between the two digits' IREDs. Maximal grip aperture was therefore measured when the distance between the thumb and index finger's IRED was maximal. This measure reveals the aperture safety margin used by participants; this margin is crucial in reach-to-grasp actions because it controls collision avoidance (Mon-Williams & Bingham, 2011). The hand and object's speeds as well as their movement durations were measured with the wrist and object's IREDs data respectively. The speed at which one approaches an object is thought to be a good reflection of their confidence, as well as the time spent to reach a given object. Moreover it reflects people's efficiency in targeting a reach-to-grasp action. IREDs were considered in motion for a velocity above 50 mm/s as per Munro et al. (Munro et al., 2007). The critical threshold for IRED velocity determined the onset and offset times of the hand and object, respectively time at which the hand or object IRED's velocity exceeded 50 mm/s and moment the IRED's velocity dropped below the threshold. The chronology of the onset and offset times of the hand and object allowed the distinction between two different movements. If the wrist velocity did not go below the velocity threshold before the onset of the object, then a 'fly-through' movement was observed; otherwise the movement was considered as a 'stop-and-go' movement. The selection of either of these approach types can be done by the user consciously or unconsciously. In Flatters' et al (Flatters et al., 2012) study, a low friction surface forced young adults into more sequential reach-to-grasp movements reflected by the 'stop-and-go' approach; the present experiment investigates whether such behaviour is observed on an older population.

The movement time, being the duration of the hand's movement until the object is picked up (i.e., in motion), is the difference between the onset time of the object's IRED and the onset time of the wrist's IRED. The time taken from the moment the wrist sets in motion until it reaches its peak speed was defined as the time to peak speed. Time to maximum grip aperture was defined as the elapsed time from the moment the wrist reaches the threshold velocity to the moment digits reach maximal grip aperture. Time to peak speed and to maximal grip aperture were normalised over the wrist's movement time to ensure that any differences were not purely a function of movement duration. Hence the normalised measures reported.

Finally, the time spent by participants to adjust their grip once they had reached the object, in the case of a 'stop-and-go' movement was named the "dwell time", and calculated as the difference between the onset time of the object and the offset time of the wrist. Therefore the kinematic measures analysed and compared were: peak speed (PS); time to peak speed (tPS); normalised time to PS (ntPS); maximum grip aperture (MGA); time to maximum grip aperture (tMGA); normalised time to MGA (ntMGA); proportion of 'stop-and-go' movements (stop); dwell time (dwell); and movement time (MT).

Taking the medium size (7 cm) stimulus in the high friction condition placed at 30 cm from the starting point as an example of a specific set of experimental conditions. Participants will start displacing their hand towards the object, starting from a null grip aperture and a null hand speed, they will accelerate the motion of their hand to reach a peak speed of about 1900 mm/s for older adults, 1000 mm/s for young adults, and 670 mm/s for young with CISG. Their PS is reached approximately 365 ms after movement initiation for older, 290 ms for young, and 345 ms for young gloved. At the same time, people are progressively widening their grip aperture to reach an MGA (maximal distance between index and thumb) of 115 mm for older, 116 mm for young, and 114 mm for young gloved. This MGA is reached 580 ms after movement initiation for older, 430 ms for young, and 580 ms for young gloved. In these conditions, the acceleration and opening phases represent respectively 19% and 32% of the overall movement time for older adults, 45% and 31% for young adults, and 15% and 42% for young adults with CISG. In a following phase, people then decelerate and reduce their grip aperture until they arrive on the object; it must be noted that the deceleration and closing phase do not necessarily match. The entire approach phase lasts approximately 1100 ms for older, 675 ms for young, and 1065 ms for young gloved. In the case where hand speed drops below 50 mm/s and a 'stop-and-go' movement occurs, then a dwell time is observed to last 210 ms for older, 165 ms for young, and 310 ms for young gloved. A summary of all the movement data and measured time and distances is given in Table 5.1.

Table 5.1 Average movement data of all the kinematic values examined in all the conditions for all the participant cohorts in the high friction condition.

			MT (ms)	MGA (mm)	tMGA (ms)	ntMGA	PS (mm/s)	tPS (ms)	ntPS	Dwell (ms)
Older adults	Close	Narrow	835	104	398	26%	373	281	17%	177
		Medium	903	118	434	27%	392	291	17%	254
		Wide	972	134	489	29%	391	281	16%	287
	Middle	Narrow	1114	96	528	31%	860	376	20%	183
		Medium	1098	115	580	32%	909	365	19%	210
		Wide	1191	133	636	37%	853	371	19%	294
	Distant	Narrow	1235	72	388	24%	1058	412	19%	173
		Medium	1331	103	601	33%	1077	411	19%	220
		Wide	1409	128	713	37%	1102	409	19%	293
Young adults	Close	Narrow	541	97	310	25%	408	230	47%	194
		Medium	548	114	314	25%	410	230	47%	157
		Wide	543	130	331	26%	427	222	43%	71
	Middle	Narrow	688	101	400	28%	1015	290	44%	186
		Medium	674	117	431	31%	994	288	45%	165
		Wide	772	131	457	33%	997	304	43%	252
	Distant	Narrow	806	105	522	35%	1439	329	43%	161
		Medium	890	120	521	36%	1382	338	41%	208
		Wide	845	133	542	37%	1445	328	41%	95
CISG	Close	Narrow	742	95	390	34%	323	381	19%	207
		Medium	836	112	439	37%	388	307	18%	312
		Wide	904	129	433	37%	296	244	16%	262
	Middle	Narrow	1044	98	510	37%	635	392	18%	409
		Medium	1065	114	584	42%	664	345	15%	310
		Wide	1228	123	579	43%	673	329	16%	279
	Distant	Narrow	1241	89	526	40%	958	385	17%	299
		Medium	1383	100	603	42%	892	411	18%	404
		Wide	1425	119	717	48%	893	405	18%	484

5.2 Analysis

The analysis was run around the data of three different population cohorts. The first set of data came from the study of Flatters et al. run on 12 young adults, exploring how the variation in object properties altered the structure of a reach-to-grasp movement. Their study confirmed the findings of Mon-Williams and Bingham by observing two different movement patterns: a 'stop-and-go' motion and a 'fly-through' motion. Flatters' et al. study and the one presented in this chapter used the same protocol and objects. However there are two differences in procedure between the two studies. Firstly, Flatters tested three different surface friction conditions, and found that little differences in terms of reach-to-grasp action structure existed between as machined surfaces and sand paper surfaces, hence the withdrawal of the as machined objects in the present study, to focus on the largest difference in friction. Secondly, they only sampled participants from a younger population.

Two population cohorts were investigated in this research. The first cohort sampled participants from what is commonly referred to as the older population, all the subjects sampled from that population were aged 60 or over. The second was constituted of young adults similar to Flatters' et al., but here participants were asked to wear CISG on their dominant hand, which was used to perform the reach-to-grasp actions required for the experiment. Analysing the effects of reduced dexterity on young adults would give clarification on the specific part dexterity losses have on older adults' behaviour. The set of data for each cohort was analysed individually in an attempt to picture the structure of reach-to-grasp action for all of these populations. In a second time, all data sets were compared, first in pairs and then all combined, to observe any possible differences in reach-to-grasp between the sampled populations, and therefore observe any potential effects of age or loss of hand dexterity. Observing young adults' performances with CISG on their hand is expected to reveal a pre-contact movement's structure similar to the one of older people, because their hand dexterity is significantly reduced by CISG.

For statistical purposes, in every condition participants had to record ten successful lifts before moving on to the next condition. The objects were designed as explained earlier to be demanding in terms of targeting and collision avoidance. Consequently some conditions were difficult for some participants who struggled to repetitively perform lifts in a given condition. As explained in Section 5.1, an attempt was considered as unsuccessful (i.e., a 'drop') when people knocked the object over, could not secure the object in the time allocated, or when the object slipped out of their grasp unintentionally whether they had managed to lift it or not. Even if the aged and CISG cohort exhibited more struggle, these evaluation conditions were kept identical for every participant. The object had to be kept stable in the air until the recording was over. In the case where 15 unsuccessful attempts where observed before ten successful ones were recorded, the test was abandoned and the condition skipped, no data was then kept for that particular participant for that precise condition. For the young adults with CISG, the test was abandoned after ten unsuccessful attempts instead of 15. It was observed that out of all the trials from all the older and young adults, only in three cases out of 432, participants dropped the object 10 or 11 times and still succeed in recording ten successful lifts. Therefore in a large majority of trials people never reached ten drops, and if they did they were almost certain to drop it 15 times and fail the test. For that matter, and due to time constraint the number of maximal allowed drops was reduced from 15 to 10 for the young adults wearing CISG.

For each cohort a repeated measures ANOVA (distance (3) x object width (3)) was carried out on each kinematic measure averaged across the ten trials recorded per condition for each participant. In order to identify the significance of the possible effects of age and dexterity loss, repeated measures ANOVA paired by cohorts were also run. Partial eta squared (η^2) values are reported for statistically significant findings. The data were tested for violations of sphericity and, where the assumption of sphericity was not met, Greenhouse-Geisser corrections (ε) were applied to the degrees of freedom. The variability of the reported measurements is graphically represented as error bars in this chapter. They are a representation of the standard error of the mean (SEM), which is calculated with the sample standard deviation divided by the square root of the sample size.

5.3 Results

The effects of object distance and width on each of the selected metrics were first analysed separately for each population cohort and separately for both surface frictions. Then relations were made between all the populations to determine the effects of age and dexterity loss. The first observations were set on the percentage of drops (i.e., number of unsuccessful attempts over the maximum number of unsuccessful attempts permitted). The number of failed trials (i.e., test skipped due to too many attempt failures before enough successful ones) is also reported.

Proportion of Dropped and Failed Trials

It must be reminded that older and younger adults had a maximum of 15 drops allowed while the gloved participants only 10. However, in order to compare effectively the proportion of drops over the maximal allowed number between cohorts, the maximal number of drops was considered as being 10 for all. In the case where the number of drops exceeded 10 then only the first 10 drops were accounted for.

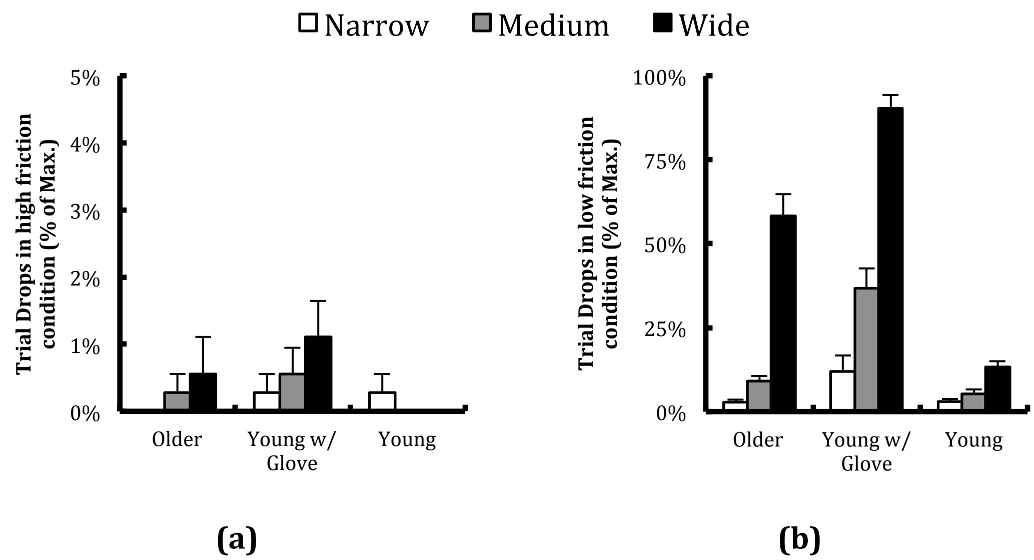


Figure 5.3 Proportion of drops over the maximal allowed number of drops grouped by object width (a) in the high friction condition, and b) in the low friction condition.

In the low friction condition, further ($F(2,22) = 4.678$, $p < 0.05$, $\eta^2 = 0.298$) and wider ($F(2,22) = 8.321$, $p < 0.01$, $\eta^2 = 0.431$) objects caused young people with no CISG more difficulty, because they bumped into or dropped the object on more occasions in this condition. However, the number of those unsuccessful attempts remained extremely low (Figure 5.3(b)). Because they almost never dropped the object in the high friction condition, no statistical analysis could be run on the drops data in the high friction condition (Figure 5.3(a)). This high success rate in both friction conditions led to the complete inexistence of failed trials (Figure 5.4). This reveals that young participants were extremely effective in all conditions, even if the proportion of drops minutely increased with object width in the low friction condition, suggesting an increasing struggle with object width.

In the low friction condition, wider objects ($F(2,22) = 28.103$, $p < 0.01$, $\varepsilon = 0.549$, $\eta^2 = 0.719$) caused older adults more difficulty. However, the number of those unsuccessful attempts remained extremely low, except for the widest object (Figure 5.3(b)). The high number of drops for the slippery wide object resulted in a fourth of all older people failing this trial condition (Figure 5.4). Again, due to the extremely low number of drops in the high friction condition (Figure 5.3(a)), no statistical analysis could be run on the drops data in the high friction condition. It shows that, even if less successful than young adults, older people at first sight appear very effective.

In the low friction condition, wider objects ($F(2,22) = 44.986$, $p < 0.01$, $\eta^2 = 0.804$) caused young adults with gloves more difficulty (Figure 5.3(b)). The number of drops was especially significant for the widest object, where subjects almost reached every time the maximal number of allowed failure. Indeed CISG forced a low success rate in the young adult population. The proportion of drops was scaled to object width in the low friction condition, and drops remained too rare in high friction to run tenable statistical analysis (Figure 5.3(a)), even. The high numbers of drops in the low friction condition led to failed trials in all width conditions for the low friction objects (Figure 5.4).

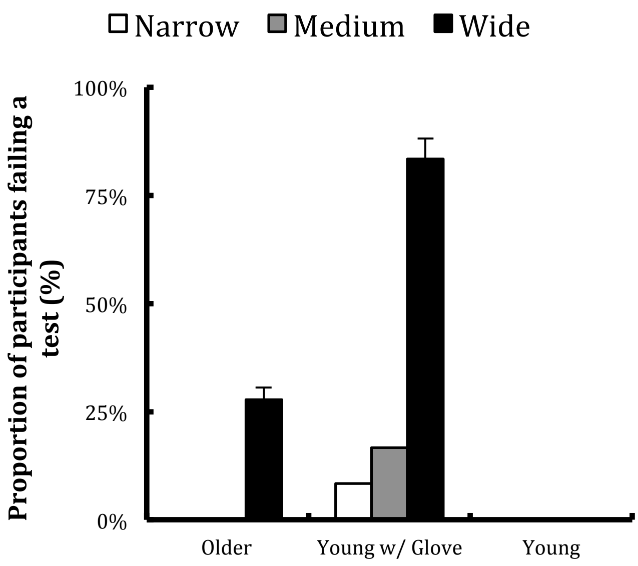


Figure 5.4 Percentage of participants who failed to secure enough lifts in the low friction condition grouped by object width.

While they were frequent in the low friction condition, drops were extremely rare if not non-existent in high friction; leading to no failed trials observed for all of the three groups in this surface friction condition. However in the low friction condition, while there were no failed trials for Flatters' group, the older cohort had a 9.30% failure rate and the young cohort wearing CISG a 36.11% failure rate averaged across all trials. The differences in reach-to-grasp difficulty in the low friction condition between groups as the object widened were reflected by the significant interactions between age and width ($F(2,44) = 13.930$, $p < 0.01$, $\varepsilon = 0.537$, $\eta^2 = 0.388$), and between glove and width ($F(2,44) = 35.731$, $p < 0.01$, $\eta^2 = 0.619$).

All cohorts were thus very successful in grasping high friction objects. Although a quarter of all older people failed low friction and wide trials, older and young adults were reasonably successful in the low friction condition. CISG drastically dropped the success rate of young adults for all trials, but most significantly for the wide low friction object. Age only seemed to cause disproportionate difficulties with the wide low friction object, while the gloves handicapped the young participants for every width, with almost all participants failing to successfully grasp the wide low friction object. The mechanism of grasp, as explained in Chapter 3, demonstrates that a secure grasp is more easily reached on high friction objects, and that wide objects are more difficult to grasp. The observed results corroborate the theoretical explanations stating that a narrower cone of friction drastically increases prehension difficulty especially for wide objects. Furthermore there was no effect of hand size on the proportion of drops, exhibiting that the differences in struggle observed were not a consequence of smaller hands. Low friction conditions caused greater difficulties resulting in a large amount of failed trials, and thus of missing data for that condition. As a consequence only the kinematic measures for the high friction conditions could be statistically analysed and compared. Only speculations can be drawn from the low friction condition data.

High Friction Objects: Movement Time (MT)

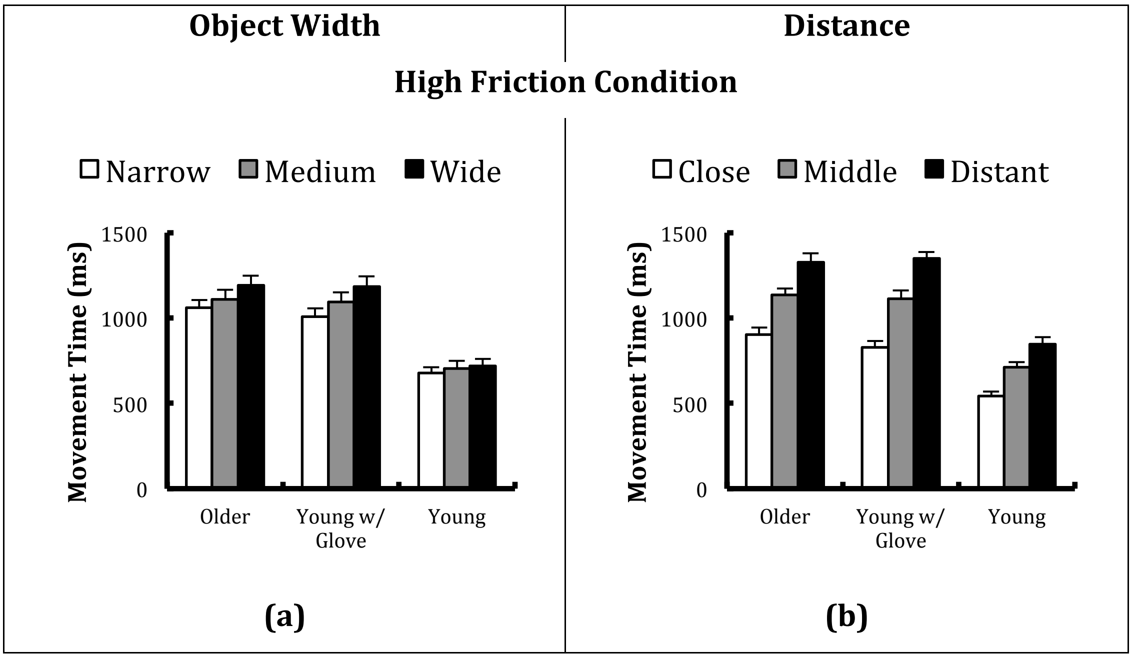


Figure 5.5 Average Movement Time values for each participant group grouped by (a) object width or (b) object distance in the high friction condition.

There was a significant effect of distance ($F(2,22) = 31.850$, $p < 0.01$, $\varepsilon = 0.550$, $\eta^2 = 0.743$), but no significant effect of object width ($F(2,22) = 0.847$, $p = 0.404$, $\varepsilon = 0.664$) on the overall movement time of young adults. Further objects forced young people in having a longer MT.

There was a significant effect of distance ($F(2,22) = 103.857$, $p < 0.01$, $\eta^2 = 0.904$) and object width ($F(2,22) = 8.455$, $p < 0.01$, $\eta^2 = 0.435$) on the overall movement time of older adults. Further and wider objects caused older people to have a longer MT.

There was a significant effect of distance ($F(2,22) = 96.156$, $p < 0.01$, $\eta^2 = 0.897$) and object width ($F(2,22) = 5.150$, $p < 0.05$, $\varepsilon = 0.578$, $\eta^2 = 0.319$) on the overall movement time of young adults with CISG. Further and wider objects caused young people wearing CISG in having a longer MT.

Paired repeated measures analyses (i.e., young vs. older, young vs. glove, older vs. glove) were run to determine the importance of the effects of age and gloves. They revealed that older participants and young participants wearing the CISG (i.e., the gloved group) did not have significantly different MT ($F(1,22) = 0.77$, $p = 0.784$); both groups had MT longer than young participants. There was a significant interaction between distance and glove for the young groups ($F(2,44) = 8.371$, $p < 0.01$, $\eta^2 = 0.276$). The increase in object distance caused the older adults and the gloved participants a disproportionate increased scaling of MT.

As predicted, as the object was placed further from the user the movement time (i.e., time to reach the object) was longer for all people (Figure 5.5(b)). However it is interesting to notice that with wider objects, forcing a larger grip aperture, the movement time was also longer, with the exception of free-handed young adults who could keep their MT constant with different object widths (Figure 5.5(a)). Additionally age and CISG seem to have a similar effect on MT, because free-handed young adults spent less time reaching for the object than the other two population groups, whose MT were within a close range across trials.

High Friction Objects: Proportion of 'Stop-and-Go' Movements and Dwell Time

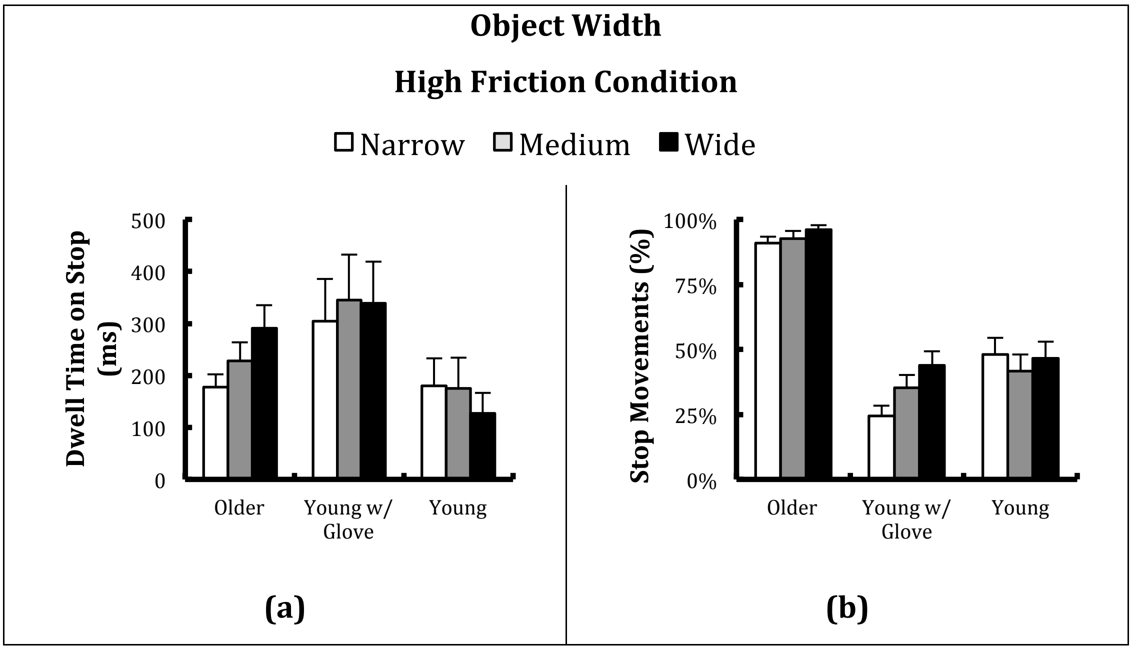


Figure 5.6 Average (a) Dwell Time and (b) 'Stop-and-go' movements values for each participant group grouped by object width in the high friction condition.

There was no significant effect of distance ($F(2,22) = 1.324$, $p = 0.287$), or object width ($F(2,22) = 2.123$, $p = 0.144$) on the proportion of 'fly-through' movements for young adults. Young adults were constant in their reach-to-grasp action's structure, because they stopped to secure their grip on half of their attempts across all trial conditions. Similarly, on those stopped attempts, distance ($F(2,12) = 1.553$, $\varepsilon = 0.514$, $p = 0.259$), and width ($F(2,12) = 0.511$, $\varepsilon = 0.502$, $p = 0.502$) had no significant effect on their dwell time (i.e., time spent adjusting grip around object before lifting it).

There was no significant effect of distance ($F(2,22) = 0.073$, $p = 0.818$, $\varepsilon = 0.557$), or object width ($F(2,22) = 2.093$, $p = 0.147$) on the proportion of 'fly-through' movements for older adults. Older people were constant in their reach-to-grasp action's structure, because they almost inevitably stopped to secure their grasp at every attempt. Similarly, distance had no significant effect on their dwell time ($F(2,22) = 0.287$, $p = 0.754$), however object width had a significant influence ($F(2,22) = 6.629$, $p < 0.01$, $\eta^2 = 0.376$). Older people spent more time adjusting their grip around wider objects.

There was a significant effect of object width ($F(2,22) = 6.269$, $p < 0.01$, $\eta^2 = 0.363$), but not of distance ($F(2,22) = 1.888$, $p = 0.175$) on the proportion of 'fly-through' movement for young adults wearing CISG. The wider the object was, the more gloved participants tended to stop near the object before lifting it. Furthermore, distance ($F(2,6) = 1.806$, $p = 0.243$) and object width ($F(2,6) = 1.274$, $p = 0.346$) had no significant effect on their dwell time either.

There were no significant differences in proportion of 'stop-and-go' movements between the two young groups ($F(1,22) = 0.798$, $p = 0.381$), whose movements were significantly less sequential than older people ($F(2,33) = 18.903$, $p < 0.01$, $\eta^2 = 0.534$; Figure 5.6(b)). There was a significant interaction between width and CISG ($F(2,44) = 6.133$, $p < 0.01$, $\eta^2 = 0.218$). With wider objects participants wearing gloves stopped more of their reach-to-grasp-and-lift movements, while free-handed young ones kept a more constant proportion of 'stop-and-go' movements. There was an interaction between age and object width ($F(2,34) = 4.096$, $P < 0.05$, $\varepsilon = 0.714$, $\eta^2 = 0.116$) for dwell time, reflecting that around wider objects older adults increased the time needed to adjust hand position while young adults decreased theirs (Figure 5.6(a)).

Object distance and width had only little effects on the structure of reach-to-grasp action in terms of 'fly-through' and 'stop-and-go' motions for people of all ages and dexterities. Nevertheless older people did need more time to secure their grip around wider objects, while CISG forced people to stop more around wider objects. Older people almost always adopted a sequential approach, far more frequently than young adults did even with a hand impaired by CISG. When performing a 'stop-and-go' movement, people with CISG needed a large amount of time to secure their grip, more than older adults, and significantly more than free-handed young adults.

High Friction Objects: Maximum Grip Aperture (MGA) and Time to Maximum Grip Aperture (tMGA)

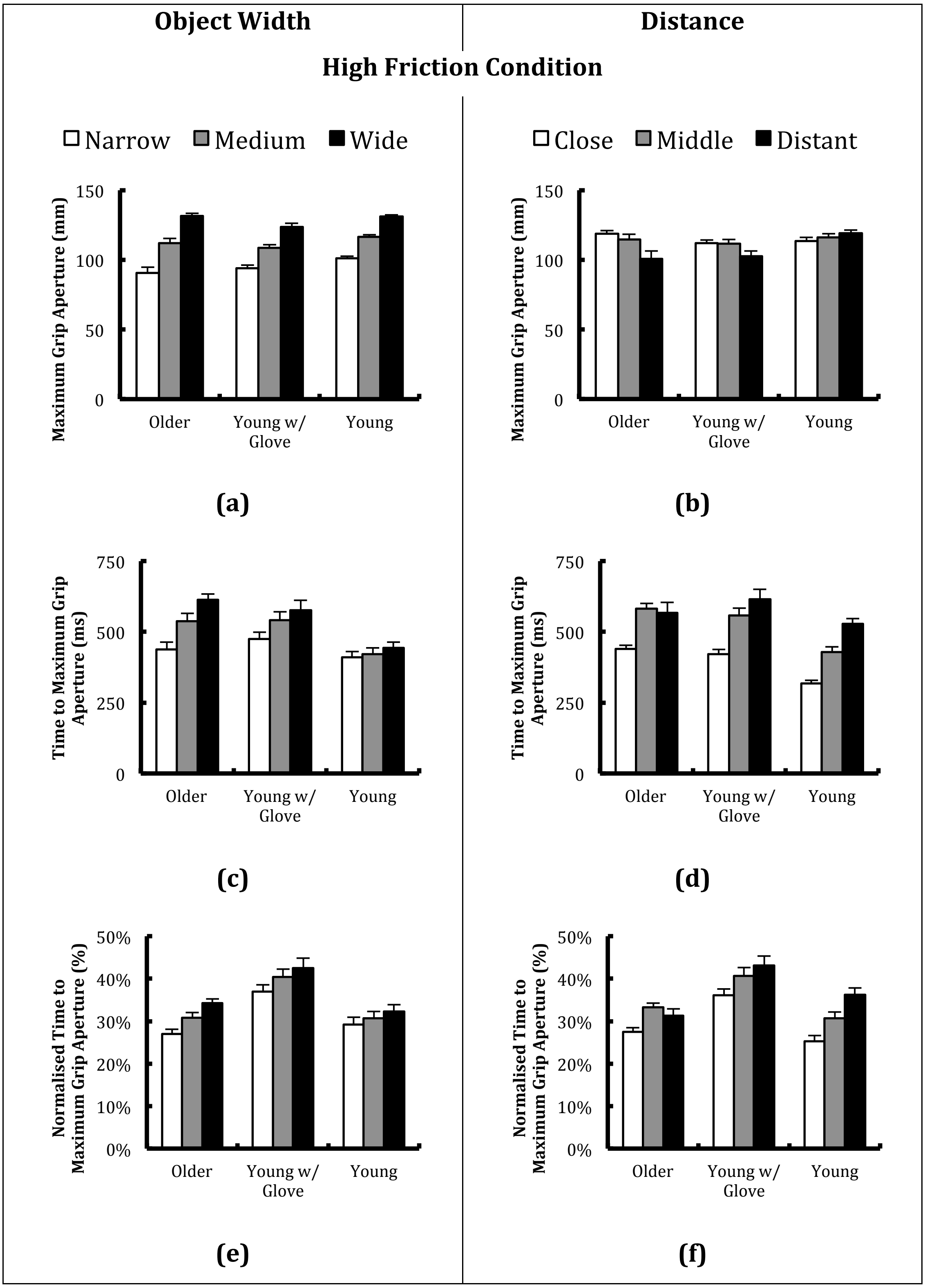


Figure 5.7 Average MGA, tMGA, and ntMGA values for each participant group grouped by object width or object distance in the high friction condition.

There was a significant effect of distance ($F(2,22) = 12.723$, $p < 0.01$, $\eta^2 = 0.536$), and width ($F(2,22) = 346.045$, $p < 0.01$, $\varepsilon = 0.586$, $\eta^2 = 0.969$) on the maximal grip aperture of free-handed young adults. Similarly, distance ($F(2,22) = 56.333$, $p < 0.01$, $\eta^2 = 0.837$) and width ($F(2,22) = 3.892$, $p < 0.05$, $\eta^2 = 0.261$) had a significant effect on their tMGA. The normalised time to Maximum Grip Aperture, or tMGA over the duration of the hand movement, was also affected by distance ($F(2,22) = 27.374$, $p < 0.01$, $\varepsilon = 0.596$, $\eta^2 = 0.714$) and width ($F(2,22) = 5.420$, $p < 0.05$, $\eta^2 = 0.326$). As the object got wider and was placed further away from them, free-handed young adults widened their MGA and took more time to reach MGA. In addition, the proportion of their aperture-opening phase over their reach-to-grasp action increased with object distance and width.

There was a significant effect of distance ($F(2,22) = 9.663$, $p < 0.01$, $\eta^2 = 0.468$), and width ($F(2,22) = 62.987$, $p < 0.01$, $\eta^2 = 0.851$) on the MGA of older adults. Similarly, distance ($F(2,22) = 6.911$, $p < 0.05$, $\varepsilon = 0.654$, $\eta^2 = 0.386$), and width ($F(2,22) = 14.101$, $p < 0.01$, $\eta^2 = 0.562$) had a significant effect on their tMGA. The normalised time to Maximum Grip Aperture was also affected by distance ($F(2,22) = 4.733$, $p < 0.05$, $\varepsilon = 0.583$, $\eta^2 = 0.301$) and width ($F(2,22) = 10.338$, $p < 0.01$, $\eta^2 = 0.485$). As the object got wider and was placed further away from them, older adults took more time to reach MGA, and the proportion of their aperture-opening phase over their reach-to-grasp action increased, with slight inconsistency with the furthest distance. In addition, with wider objects older people widened their MGA, however they narrowed it with greater distances.

There was a significant effect of distance ($F(2,22) = 7.930$, $p < 0.01$, $\eta^2 = 0.419$), and width ($F(2,22) = 41.853$, $p < 0.01$, $\varepsilon = 0.555$, $\eta^2 = 0.792$) on the MGA of young adults wearing CISG. Similarly, distance ($F(2,22) = 11.713$, $p < 0.01$, $\varepsilon = 0.660$, $\eta^2 = 0.516$) and width ($F(2,22) = 6.093$, $p < 0.01$, $\eta^2 = 0.356$) had a significant effect on their tMGA. The normalised time to Maximum Grip Aperture was also affected by distance ($F(2,22) = 5.233$, $p < 0.05$, $\eta^2 = 0.323$) and width ($F(2,22) = 5.697$, $p < 0.05$, $\varepsilon = 0.592$, $\eta^2 = 0.343$). As the object got wider and was placed further away from them, young adults with gloves took more time to reach MGA, and the proportion of their aperture-opening phase over their reach-to-grasp action increased. In addition, with wider objects young people with CISG widened their MGA, however they narrowed it with greater distances.

Even though MGA was the only kinematic value, with dwell time with no significant difference between groups, there was a significant interaction between age and distance ($F(2,44) = 15.100$, $p < 0.01$, $\eta^2 = 0.407$) and between glove and distance ($F(2,44) = 15.153$, $p < 0.01$, $\eta^2 = 0.408$). This gives that with increasing distance people's MGA decreased for older and gloved participants, but increased for young ones (Figure 5.7(b)). Every group scaled their grip aperture to the object width (a larger aperture for a larger object), yet older people used larger grip aperture steps between objects than young adults did ($F(2,44) = 3.881$, $p < 0.01$, $\eta^2 = 0.150$; Figure 5.7(a)). The supposition that it would take participants more time to reach distant objects and therefore more time to reach MGA was verified (Figure 5.7(d)). Similarly, MGA was reached later for wider objects (Figure 5.7(c)). Older and gloved participants reached MGA later than young people ($F(2,33) = 7.662$, $p < 0.01$, $\eta^2 = 0.317$), with no significant differences in tMGA between older people and young people wearing gloves ($F(1,22) = 0.003$, $p = 0.957$). There was a significant interaction between age and object width ($F(2,44) = 8.356$, $p < 0.01$, $\eta^2 = 0.275$) for tMGA, showing that older people scaled the time they spent opening their grip to the object width with large gap differences while young adults used significant lower steps. Proportionally to the movement time of their wrist, older participants and free-handed young participants reached MGA significantly earlier than young gloved participants ($F(2,33) = 7.015$, $p < 0.01$, $\eta^2 = 0.298$; Figure 5.7(e), (f)), since there was no significant difference between free-handed young and older subjects' ntMGA ($F(1,22) = 0.000$, $p = 0.988$).

Evidently people of all ages and dexterities positively scaled their MGA to object width, but they might scale it in different ways to distance. As it was expected, increasing the distance increased the overall movement time and the time to reach MGA for everyone. Because increasing the width of the object forces an increase in MGA, it is logical that it also increased the time necessary to reach MGA. Moreover, everyone scaled their opening and closing phases to distance and object width, except the older adults who did not scale their ntMGA to distance. In general, with distant objects longer opening phase could be observed, similarly with wider objects.

High Friction Objects: Peak Speed (PS) and Time to Peak Speed (tPS)

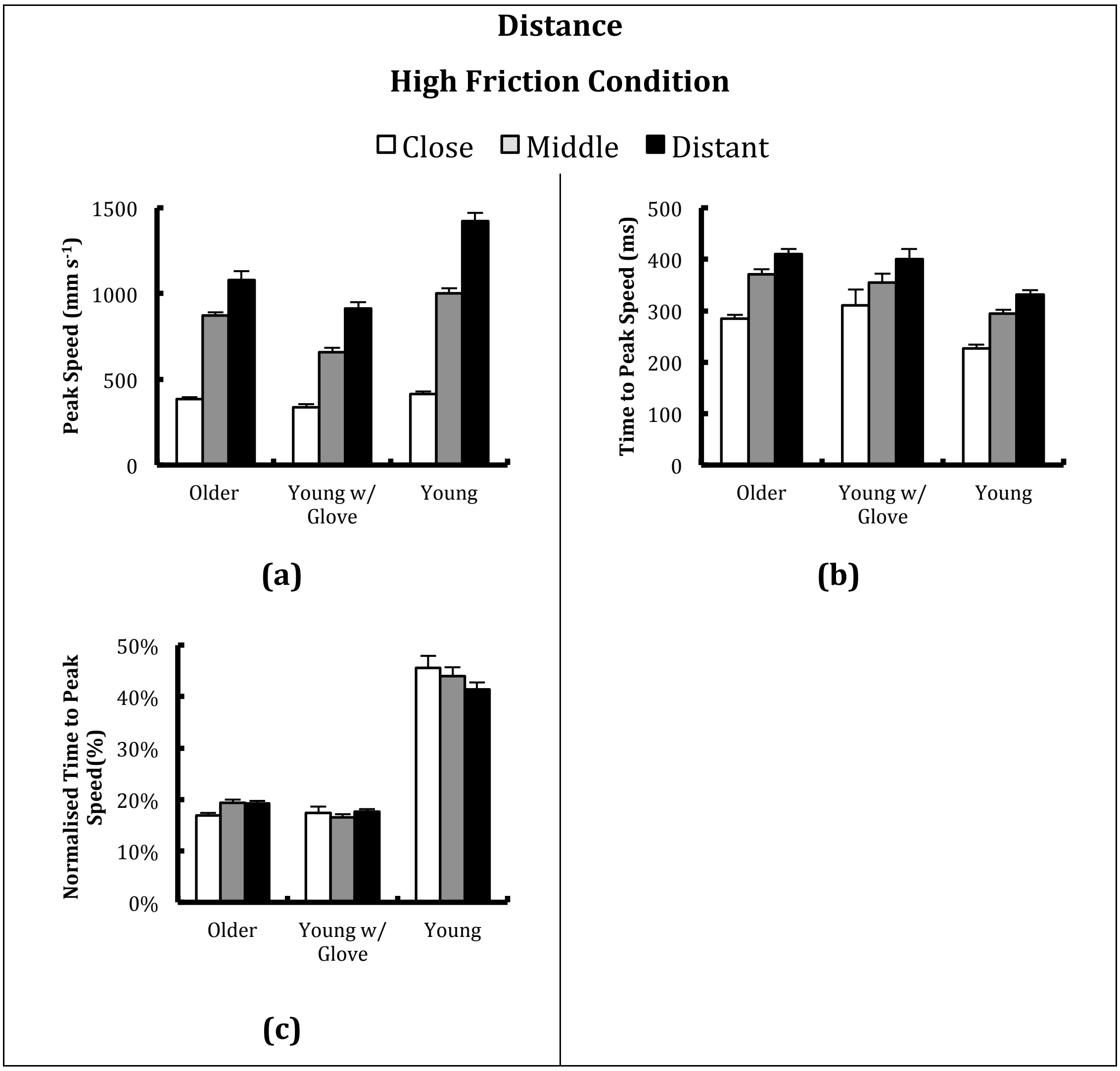


Figure 5.8 Average PS, tPS, and ntPS values for each participant group grouped by object distance in the high friction condition.

There was a significant effect of distance ($F(2,22) = 207.151$, $p < 0.01$, $\varepsilon = 0.536$, $\eta^2 = 0.950$), but not of width ($F(2,22) = 1.843$, $p = 0.182$) on the peak speed of free-handed young adults. Similarly, distance had a significant effect on their tPS ($F(2,22) = 151.633$, $p < 0.01$, $\eta^2 = 0.932$), but not object width ($F(2,22) = 0.161$, $p = 0.853$). The normalised time to Peak Speed, or tPS over the duration of the hand movement, was affected by neither distance ($F(2,22) = 2.738$, $p =$

0.117, $\varepsilon = 0.610$) nor width ($F(2,22) = 1.169$, $p = 0.313$, $\varepsilon = 0.623$). As the object was placed further away from them, free-handed young adults raised their PS and took more time to reach it. However, the ratio of their acceleration and deceleration phases did not suffer significant changes across trials. The object width had absolutely no effect on any of the free-handed young adults' peak speed metrics, and thus they did not suffer any significant changes across width trials.

There was a significant effect of distance ($F(2,22) = 51.956$, $p < 0.01$, $\varepsilon = 0.529$, $\eta^2 = 0.825$), but not of width ($F(2,22) = 3.261$, $p = 0.058$) on the peak speed of older adults. Similarly, distance had a significant effect on their tPS ($F(2,22) = 99.373$, $p < 0.01$, $\eta^2 = 0.900$), but not object width ($F(2,22) = 0.166$, $p = 0.848$). The ntPS was also affected by distance ($F(2,22) = 15.667$, $p < 0.01$, $\eta^2 = 0.600$), but not by width ($F(2,22) = 2.779$, $p = 0.084$). As the object was placed further away from them, older adults raised their PS and took more time to reach it. In addition, the proportion of their acceleration phase over their reach-to-grasp action increased with object distance. The object width had absolutely no effect on any of the older adults' peak speed metrics, and thus they did not suffer any significant changes across width trials.

There was a significant effect of distance ($F(2,22) = 92.341$, $p < 0.01$, $\varepsilon = 0.679$, $\eta^2 = 0.894$), but not of width ($F(2,22) = 0.464$, $p = 0.635$) on the peak speed of young adults with CISG. Distance had no effect on their tPS ($F(2,22) = 2.436$, $p = 0.134$, $\varepsilon = 0.673$), nor did object width ($F(2,22) = 2.097$, $p = 0.169$, $\varepsilon = 0.617$). The ntPS was affected by neither distance ($F(2,22) = 0.280$, $p = 0.644$, $\varepsilon = 0.591$) nor width ($F(2,22) = 0.441$, $p = 0.649$). As the object was placed further away from them, young adults with gloves raised their PS, but did not seem to take more time to reach it. Furthermore, the ratio of their acceleration and deceleration phases did not suffer significant changes across trials. The object width had absolutely no effect on any of the gloved people's peak speed metrics, and thus they did not suffer any significant changes across width trials.

Young people had a larger peak speed than older people who themselves had a slightly larger PS than young adults with CISG ($F(2,33) = 14.388$, $p < 0.01$,

$\eta^2 = 0.466$; Figure 5.8(a)). There was a significant interaction between distance and age ($F(2,44) = 6.969$, $p < 0.01$, $\varepsilon = 0.574$, $\eta^2 = 0.241$), and between distance and CISG ($F(2,44) = 21.782$, $p < 0.01$, $\varepsilon = 0.594$, $\eta^2 = 0.498$), reflecting reduced scaling of movement speed to more distant objects for both older adults and gloved participants. The peak speed data of young people with gloves was here again closer to the data of older people than to the one of the young people. Older people and young gloved had a longer time to peak speed than free-handed young adults ($F(1,22) = 0.000$, $p = 0.999$; Figure 5.8(b)). Yet older people and young adults with gloves, reached peak speed significantly earlier in their hand movement than free-handed young adults across all trials ($F(2,33) = 73.250$, $p < 0.01$, $\eta^2 = 0.816$; Figure 5.8(c)). There was a significant interaction between distance and age for ntPS ($F(4,66) = 3.257$, $p < 0.05$, $\varepsilon = 0.634$, $\eta^2 = 0.165$), with younger adults reaching peak speed much later in the movement.

Free-handed young adults reached higher hand speed in a reach-to-grasp action than older people and young adults wearing CISG (Figure 5.8(a)). As it was suspected, the more distant the object was the more time it took people to reach it, and consequently the more time it took them to reach PS, with the exception of gloved participants who showed no statistical difference across trials (Figure 5.8(b)). Figure 5.8(b) shows though that gloved participants appeared to also be scaling their tPS to object distance, it is thought that the statistical analysis did not reveal it as significant because of the large variance. In relation to the duration of their hand movement younger adults reached peak speed much later (approximately half way through the movement) than older adults or young adults with CISG (Figure 5.8(c)). Their pre-contact movement had a longer acceleration phase and shorter deceleration phase than the other two groups.

As explained earlier, there was a high rate of failure in the low friction condition resulting in little data collected, hence a low statistical power. No inference could be drawn from a statistical analysis of such underpowered sample. Nevertheless speculations can be drawn from the existing low friction data and comparisons made with the high friction data. Across all trials and population groups MT seemed to be scaled to object width (Figure 5.9(a)) and distance (Figure 5.9(b)) similarly to the high friction condition, while being approximately twice as long in low friction. On 'stop-and-go' movements, participants appeared to have spent more than twice as much time adjusting their grip before picking the object up in the low friction condition (Figure 5.9(c), (d)). Interestingly dwell time appeared to be scaled to distance and not width. The values and evolution across trials of MGA, tMGA, ntMGA, PS and tPS seemed to be equivalent in both friction conditions. However ntPS on low friction objects for free-handed young appeared to be half of what it was on high friction objects (Figure 5.9(f)). Finally, in the high friction condition older people almost never performed a 'fly-through' movement, whereas young adults, with and without CISG, only stopped 25% to 50% of the time. It appeared that in the low friction condition all cohorts struggled more, since they all always seemed to stop their movement before picking the stimulus up (Figure 5.9(e)).

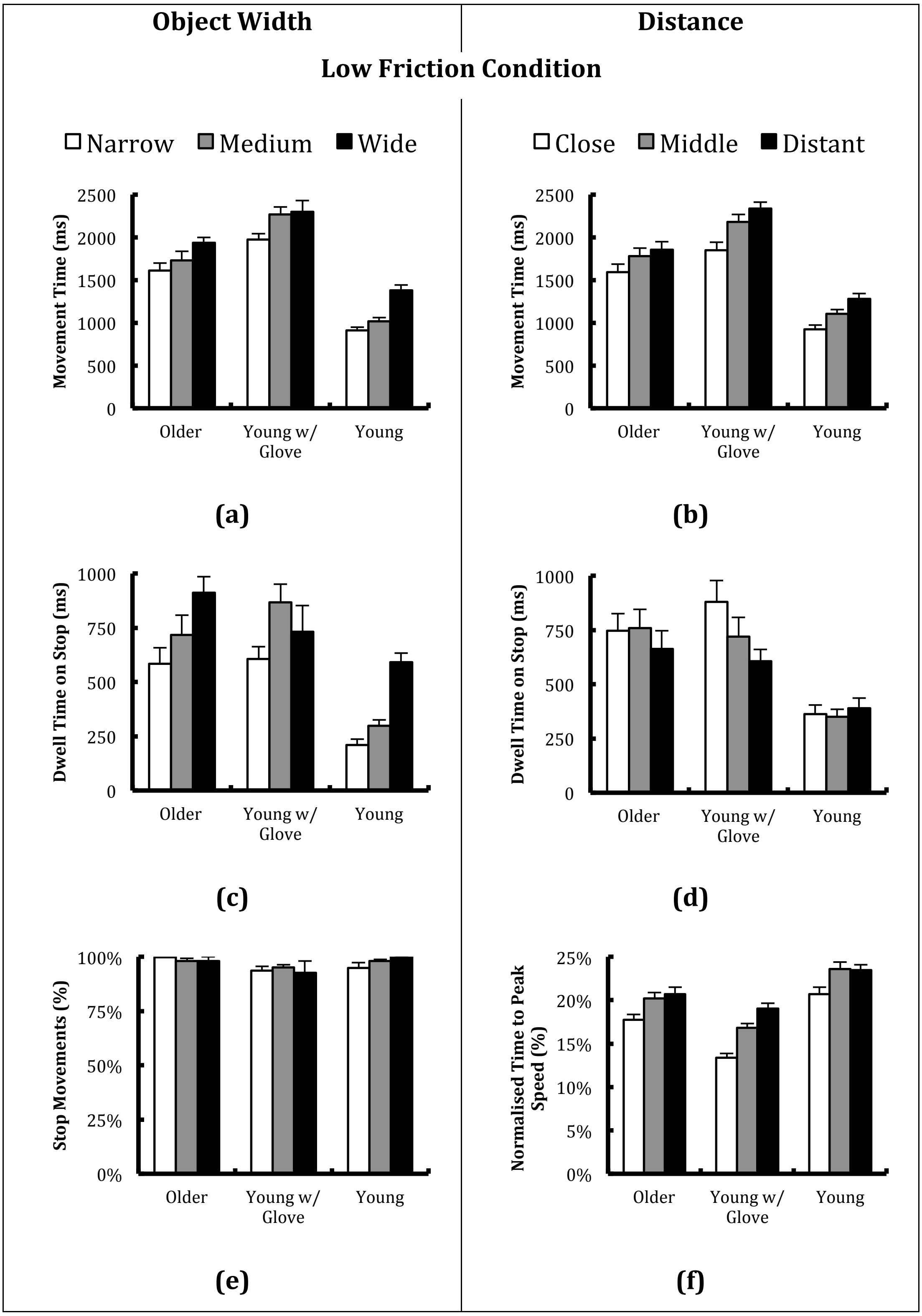


Figure 5.9 Average kinematic values for each participant group grouped by object distance or object width in the low friction condition.

To summarise, drops rarely occurred in the high friction condition but were frequent in the low friction condition. More than a quarter of the older population could not successfully reach, grasp, and lift the wide stimulus in low friction conditions, and more than four in five young adults could not do it with CISG on. The object, being unstable, could easily be knocked over and participants struggled to grasp low friction objects in the few seconds they were allocated with to perform the task. Similarly to the proportion of failure, with wider objects more drops were observed for older and gloved people. In the most extreme width condition age seemed to increase the difficulty in achieving a successful reach-to-grasp-and-lift movement on unbalanced low friction objects. However the CISG disproportionately increased that difficulty for every object width, to the point where for the widest object almost all of the participants failed the test. Increasing the width of the object increased the difficulty for every group. Age or dexterity loss amplified to different degrees this difficulty. Interestingly, increasing the object distance decreased the difficulty for young adults with CISG. If given space people were better at coping with the handicap of the glove.

5.4 Discussion

5.4.1 Reach-to-Grasp Structure

Consciously or unconsciously, people construct their reach-to-grasp whether as a continuous motion called 'fly-through', or as a sequential one called 'stop-and-go', where they pause their movement to secure their grip (Mon-Williams & Bingham, 2011). Friction, distance and size influence the structure people adopt (Flatters et al., 2012). Reproducing Flatters' study with older people and young people equipped with CISG allowed kinematic data comparisons to determine the respective effect of age and dexterity loss on a reach-to-grasp-and-lift action.

When presented with a low friction object people of all ages and dexterities inevitably stop to secure their grip around the object before lifting it up, across all object widths and distances. Together with a high proportion of drops (e.g. the object slips out of grasp or is knocked over), this reveals the increased difficulty that low friction generates. While older people almost never perform 'fly-through' movements, regardless of the friction, width, or distance condition, no prediction could be made on whether a specific condition would result in a ‘fly-through’ motion for both young cohorts in the high friction condition. And yet scaled numbers of ‘stop-and-go’ approaches to object width were observed for gloved participants, indicating that for wider objects the likelihood for a ‘stop-and-go’ motion was higher. In the high friction condition, older people use more time to secure their grip with increasing object width, while young adults do not stop their movement often enough to observe any significant effect on their dwell time. In the low friction condition the dwell time appear to be scaled to object width more evidently than in the high friction condition for all the population cohorts. It is hypothesised that younger adults might scale their dwell time to object width if the object present some risk of slippage. Users might need more time to secure their grip as the object width increases, because it increases the difficulty of the lifting task.

In the low friction, participants wearing CISG were very ineffective across all widths, and dropped the object at almost every attempt with the widest object. Across all participants and for both friction conditions the number of involuntary drops increased with object width. Considering that the proportion of dropped attempts is an indicator for difficulty, this demonstrates that wide objects and slippery textures make reach-to-grasp more difficult.

Observing that older people adopt a ‘stop-and-go’ movement almost every time with low friction objects as well as with high friction objects seems to indicate that the task is as difficult for them in both conditions. This first finding shows a clear difference in behaviour between the two distinct age groups. As reduced dexterity is thought to be the most impairing factor for older people, it would suggest that it is their lower dexterity that causes them such difficulty. Interestingly young adults with lowered dexterity do not reduce their number of ‘fly-through’ motions, suggesting that reduced dexterity is not the direct cause for sequential approaches. However, it may be the indirect cause. More attention and care is put in a ‘stop-and-go’ movement resulting in a more effective movement, and older people may have learned this. It may be that noticing that lower dexterity made them less effective, older people have opted (consciously or not) with practice to adopt more ‘stop-and-go’ reach-to-grasp. It can also be hypothesised that if older people stop their movement to secure their grip even in 'easy' reach-to-grasp situations (i.e., high friction condition), it is because they are more careful, but not necessarily because they struggle more. Such conduct ties in with the observations older people gave in the focus groups reported in Chapter 4.

Aware of their lower dexterity young adults wearing CISG did not opt for more 'stop-and-go' approaches, causing a high proportion of drops. This conscious of unconscious decision is likely to be the reason for the high proportion of failed attempts. This proves that with lower dexterity the task could be performed, but more care needed to be put in it, otherwise the object would frequently slip out of grip or be knocked over. It is hypothesised that because young people did not experience lack of dexterity for a long period and were not accustomed to the condition caused by the gloves, they did not change their approach, and thus failed many attempts. It would be interesting to have young participants wear the gloves for a longer period prior to the test, and see whether their pre-contact structure suffers any change compared to the present study's results. Lower dexterity is believed to decrease accuracy of reach-to-grasp, and consequently more care must be taken by adopting a 'stop-and-go' motion rather than a 'fly-through' one. The use of CISG reflects the latter observation, but the change of condition by being too sudden does not allow the users to learn and adapt their motion to it. In terms of reach-to-grasp movement type (conscious or unconscious) selection, CISG do not appear to be a tool representing ageing accurately.

5.4.2 Effects of Object Size, Friction, and Distance on Reach-to-Grasp Kinematics

The purpose of this study was to understand the effects of object distance from user, object width, and object surface friction on people's reach-to-grasp actions. It was demonstrated that those factors influence the structure of reach-to-grasp actions. The effects of each of those factors on the kinematics of people's pre-contact phase are listed in Table 5.2 and discussed in this section.

Table 5.2 Summary of the effects of the independent variables on the dependent ones. (+), (-) and (0) respectively represent a positive, negative, and inexistent relation. (*) Only speculation can be made on the effects of friction.

		MT	MGA	tMGA	%_tMGA	PS	tPS	%_tPS
Distance	Older	+	-	+	+	+	+	+
	CISG	+	-	+	+	+	+	0
	Young	+	+	+	+	+	+	0
Width	Older	+	+	+	+	0	0	0
	CISG	+	+	+	+	0	0	0
	Young	0	+	+	+	0	0	0
Friction*	Older	-	0	0	0	0	0	-
	CISG	-	0	0	0	0	0	-
	Young	-	0	0	0	0	0	-

No statistically significant effect of distance on tPS was found for gloved participants, but this result is suspected to have been affected by the large variance of the data because Figure 5.8(b) shows a clear positive scaling of tPS with distance. With further objects, people will reach higher hand speed, take more time to reach it, and more time to reach the object and maximal digit aperture. The fact that distance affects PS but not ntPS corroborates Jeannerod's observations (Jeannerod, 1984), however here distance was found to have an effect on MT. While here the precise location of IRED was used to calculate all kinematics measures, Jeannerod only based his analysis on hand movement observations on video recordings. Furthermore he did not impose any time constraints on his participants, which according to him has a strong effect on people's reach-to-grasp. Interestingly, the scaling of MGA to distance was disparate between all cohorts, but they were all affected by object distance nonetheless. In short, distance affects the duration of a movement, as well as its velocity. It also shapes the sizing and timing of the user's hand grip aperture. Additionally, when an object is distant people have space to reach higher speed, and form their grip aperture. Because their hand is not too suddenly on the object it is thought that people feel more at ease, and opt for a shorter closing phase when the object is more distant.

It was observed that as the object got wider, older people and young people with CISG took more time to reach the object. This could have been predicted because a wider object is more likely to be knocked over, and requires a wider finger aperture and thus more finger movements. It also reflects that both groups are not as effective or confident with their accuracy as free-handed young adults. The success of a pinch grip relies on the grip aperture people can form, which explains why with larger objects people create a larger grip aperture, and consequently take more time opening their grip, but also give advantage to their opening phase. This evidently demonstrates that wider objects are more difficult to grasp, and require more care. Object width is therefore an important factor dictating the accessibility of an object and ease to grasp-and-lift it.

Many subjects, especially the older people and the young adults wearing CISG struggled to successfully perform all the low friction tests. As explained earlier this resulted in a significant lack of data, and forced the study to be underpowered for that condition. It therefore needs to be highlighted that all observations made on friction condition's effects are only speculations, and cannot be taken as facts. In the high friction condition, the movement times of all subjects across all trials were 50% to 100% greater. Such behaviour tends to express a more cautious approach in reaction to a more difficult and hazardous task. In the high friction condition, the young adults reached peak speed halfway through their reach-to-grasp movement. In the low friction condition, they reduced their acceleration phase to a third of the deceleration phase, similarly to what older adults and young people with gloves had in the high as well as in the low friction condition. Interestingly the object's surface friction is speculated to have no effect on the hand approach speed of all subjects, even though people took more time to perform the trials. Lower object surface friction therefore makes the handling of a given object more difficult and hazardous, and forces people of all ages and dexterities to a longer and more cautious approach, which does not necessarily avoid a decrease of efficiency.

In addition to numerous sequential movements older people took significantly more time to reach and grasp the objects, and more time to secure their grip around it. This longer approach confirms the hypothesis that older people adopt a more cautious reach-to-grasp action than their younger counterparts. These observations supports previous research findings such as Kinoshita's, who declared that older people "*use a prolonged and cautious exploration of the object*" (Kinoshita & Francis, 1996). The gloves, in terms of movement duration, force young adults to be slower, and minimise their grip aperture margin similarly to older adults. Interestingly the drastic loss of dexterity caused by CISG does not affect the structure of people's reach-to-grasp by provoking more sequential approaches, but forces slower movements, and dwell time longer than older adults. Because people were not accustomed to the gloves they did not change the way they are used to grasp objects, and did not pause their movement to secure a lift. If the losses of dexterity were to force a careful approach people would have slowed their movement down as well as spent more time adjusting their grip. The phenomenon generated by CISG is believed to be a combination of the consequence of low dexterity, and of behavioural habits that cannot be adapted over a short period of time that is an experiment.

Wider grip aperture generates a wider aperture safety margin with the object, and reduces the risk of bumping into the object. For the two narrowest objects young adults created a large safety margin by opening their grip aperture slightly larger than necessary to avoid any risk of knocking the object over. Older people did scale their aperture to the object width, but did not use large margins for any object width. They minimised their aperture not to open their grasp more than they needed to, which was probably easier but contributed to a high likelihood of bumping into the object. The results between the two age groups matched for the wide object because it was too wide for young adults to apply a large safety margin as they did for the other two widths. As expected CISG forced young adults into scaling their grip aperture to object size in similar ways to older people. CISG seem to be a good tool to mimic old age in terms of grip aperture as long as fingers are not to be extended outward. It is hypothesised that due to lower hand dexterity older people cannot open their fingers as easily and effortlessly as young adults, and therefore minimise this effort by minimising their maximum grip aperture.

Older people and people wearing CISG took more time to lift the objects, more time to reach peak speed and MGA, had shorter acceleration phases, and lower peak speed. It is interesting to observe that the values were again very similar. This shows that both older and young adults with gloves practiced a more cautious approach, because that way they minimised the risk to arrive too quickly, or brusquely onto the object. Longer opening phase highlights that CISG produced a greater discomfort than healthy ageing, or perhaps the dexterity impairment is too distinct. Nevertheless, this showed that healthy ageing or reduced dexterity force more cautious reach-to-grasp actions. The data of the young adults wearing gloves was in general closer to the data of older adults than to the one of free-handed young adults. The present results seem to indicate that the structure of older adults' reach-to-grasp action can partly be explained by their lower dexterity compared to younger adults. CISG appear to be a good impairment simulator linking young and older adults' abilities. However, they do not accurately simulate an old person's hand that aged without developing any major impairment such as arthritis. Indeed CISG were developed to simulate conditions such as arthritis, thus the dexterity impairment they induced goes beyond what healthy ageing induces. Young people were being more cautious when wearing the gloves, and approached the object with more care. Nevertheless, they had a high rate of drops, and failures considerably more than older people themselves. The gloves are therefore not perfect replicas of ageing effects. They generate a great handicap that young adults have not learned to master, while older people have learned to cope with ageing.

The results from the high friction condition revealed numerous differences between older and young people in a reach-to-grasp-and-lift movement. Older people were found to be slower, taking more time, having more difficulties, being more hesitant, needing more time to lift objects up, and secure their grip, and they also made sure to slow their hand down as they approach an object for a more controlled and secured approach. Subsequently almost all their movements are 'stop-and-go'. At this point it is hard to distinguish whether their slower pace results from their capacities or will. This can indicates more cautious behaviour, corroborating what they admitted in Chapter 4, but it can also suggest lower aptitude. Indeed spending a lot of time adjusting fingers around an object can come from the desire to secure a grip, or the difficulty to apply one. Older people do take more care and yet do not have the success rate of young people, as shown by the wide object conditions, frequently knocked over or dropped during the experiment leading to occasional failed tests. Wider objects caused greater difficulty to the general population, but to a greater degree for older people. This is likely to be due to older people's lower dexterity stopping them from using large grip aperture safety margin as young people do. It must be reminded that the older subjects had no history of arthritis (or other medical condition that could have outrageously affected their hand grip).

To conclude, it can be hypothesised that hand dexterity is a major factor influencing older people's behaviour, and partly dictating their reach-to-grasp pace. Nevertheless young adults with reduced dexterity did not have less 'fly-through' movements, thus they were not adopting the careful reach-to-grasp structure older people used. This proves that older people's behaviour is not simply a matter of slower cognitive processing or lower physical abilities, but also of their intention to be more careful and succeed in the prehension of objects.

This chapter revealed how someone's reach-to-grasp action can be detailed and defined by a series of metrics. It revealed that people of all ages and dexterities scale their reach-to-grasp movements to object distance, width, and surface friction. A wide and slippery object is difficult to pinch grip and lift causing a slower and more sequential, hence more careful approach. Healthy ageing also has an effect on people's reach-to-grasp movements. Older adults adopt slower, more sequential approaches: more careful approaches. CISG have proved that part of older adults' behaviour comes from their lower hand dexterity. CISG have shown to be a good tool to simulate old age, but do hold some limitations. As mentioned in the introduction to this chapter, a successful grasp results from a targeted and accurate pre-contact phase, but also from a precise and stable contact phase. The contact phase in a precision grip is believed to be driven by grip force and user's adaptability to cope with perturbations. The influence that product properties, such as object size and surface friction, have on grip force is studied in the following chapter.

Chapter 6

Pinch Grip Force in Older Adults

Our hands, and opposable thumbs are what permits us to manipulate the world and gives us the dexterity to achieve what our mind is directing or conceiving. Our hand is a powerful, dextrous and precise limb, probably one of the most complex in our body. The biological structure of a human hand has been known for decades. However many aspects of what goes on during handling remains unexplored. Psychologists and product designers are working on understanding the interaction between humans and their environment, of which hand is an important actor. Chapter 5 explained how a reach-to-grasp action can be decomposed into a pre-contact and a contact phase. It showed the importance of the pre-contact phase in a successful and stable pinch grasp, while revealing the effects of age, dexterity, and certain object properties on people's reach-to-grasp motions. This phase has a crucial role in handheld tools handling, and therefore cannot be overlooked in kitchen tools development if the comfort of the user is considered.

The reaching movement inevitably leads to contact with the object and to a grasp. This phase has also an important role in the success of the grasp, and in the comfort of the user. While in the pre-contact phase, elements such as hand speed and grip aperture formation were the dictating factors, the primordial factor of the contact phase is the grip force generated on the object. Chapter 4 revealed that older people reported a loss in dexterity and grip force capacities leading to an increased difficulty in handling handheld tools, hence more difficulty in cooking. The contact phase and people's grip force capacities are therefore as important as the pre-contact phase in the success and comfort of handling. As seen in Chapter 3, the force distribution and application where the skin gets in contact with an object is far from trivial. Yet in a pinch grip, the contact of each digit can be simplified to unique contact points. The forces in action at these contact points dictate the success and stability of the grasp, based upon how well they can be adjusted to an object's properties.

At the contact area between the digit's tip and the object surface, the mechanoreceptors continuously stream afferent tactile information to the Central Nervous System (CNS) and grip forces are applied in response. Additionally, in response to change in the muscle length, muscle spindles convey static and dynamic body posture information to the CNS. This information generates an automatic response from the brain in the form of efferent signals that are transmitted to the muscle to adapt itself to the changes observed. Cutaneous signals contribute to kinaesthesia, which with intact sensory feedback is essential for accurate and efficient grip and precise adjustment of grip force (Johansson & Flanagan, 2009). Therefore the coefficient of friction of the skin/object surface is expected to have a large effect on the pinch grip force applied. The object size is also thought to have a significant effect on grip force, because grip aperture changes the orientation to which grip force can be applied. Strength capacities are known to change as one's pinch grip aperture widens. Consequently both object's size and surface friction are likely to facilitate or complicate object handling. Object width, and surface friction, the object properties studied in Chapter 5, influence the pre-contact phase of a reach-to-grasp action, and are thus also likely to influence its contact phase as well. Furthermore, as seen in Chapter 2 the literature believes that many object properties affect grasp, especially friction, and object size.

Literature has indeed favoured the contact phase of handling rather than the pre-contact phase, and has thus demonstrated how for instance different surface textures affect grip force. The work presented in this chapter is novel compared what has already been researched, partly because it studies the influence on grip force of object width and friction jointly. The attempt to replicate the greasiness that some kitchen tools might be covered with during cooking generates the study of a level of slipperiness rarely found in pinch grip force research. The objectives of this chapter are thus to reveal the effects that grip aperture and object surface friction have on maximal voluntary pinch grip force and the forces used during lifting motions. The first part of this chapter analyses the evolution of people's pinch grip force capacities between their thumb and index finger with pinch grip aperture. In a second part, the grip force people rely on to lift an object and cope with movement perturbations is studied across different objects and populations. The force safety margin people use between the force used and the minimal force required to avoid slippage is also investigated across object widths and populations. When subjected to the addition of an unexpected load stopping the object in its motion, people use that safety margin to keep hold of the object in the very first part of the perturbed movement. Observing whether people can cope tests the efficiency of their safety margin and ability to rapidly adapt their grip.

The influence of object properties on grip force was investigated in conjunction with the influence of users' age and dexterity on grip force. As applied forces are expected to differ with age, and this thesis aims at improving older people's daily life, grip force is studied in this chapter for a young and an older population.

Chapter 6 therefore reports the results of two experiments. The first experiment, referred to as the Stationary Experiment, was designed to measure the evolution of maximal grip force capacities of younger and older adults with object width and object surface friction. It also gives an estimate of the proportion of the population that will, for a given width and surface condition, be able to comfortably apply a given pinch force. The second experiment, referred to as the Perturbation Experiment, was designed to observe the grip force younger and older people apply on an object to be able to cope with unpredictable perturbations. It also presents the effects of product properties such as object friction and width on that grip force and its proportion in relation to slip force.

6.1 The Stationary Experiment: Pinch Grip Force Capacities on Stationary Object

6.1.1 Methods

Participants

In this pinch grip session on stationary objects a group of 12 young adults (age mean 28.42 years, age range 24 – 35 years; six females, 11 reported right hand preference), and a group of 12 older adults (age mean 69.25 years, age range 63 – 85 years; eleven females, 11 reported right hand preference) participated. The series of tests necessitated approximately 30 minutes. The young adults cohort performed the series of tests of the Stationary Experiment twice: once in normal conditions, and once while wearing CISG both in a single one-hour sitting. Not having to wear CISG, the older adults could perform the Stationary Experiment and the Perturbation Experiment in a one-hour single session. All participants took part in a single session lasting approximately one hour. All participants had normal or corrected-to-normal vision, and no history of neurological deficit or hand deficiency such as arthritis. Maximal pinch grip aperture (MGA) was measured for each individual (young adults group: MGA mean 14.88 cm, and range 12.0 – 19.0 cm; older adults group: MGA mean 13.26 cm, and range 11.0 – 15.5 cm). All subjects provided informed consent prior to inclusion in the study, which was approved by the University Ethics Committee, and received £5.00 for taking part in the study. They were randomly selected from a list of contacts, and recruited by email or phone. They were completely naïve with regard to the present study's purpose.

Apparatus

The goal of the apparatus was to present the participants with rounded end cylinders of varying lengths and frictions, and measure the maximal pinch force participants could apply by squeezing those by their ends. The design of the stimuli used here was similar to the design of Chapter 5's stimuli, as the measures of this chapter are in the continuity of the outcomes of the previous chapter. Both chapters' stimuli were made of hard plastic; their low friction condition was achieved with the same product brushed onto their smooth surfaces. Additionally, the diameter of the cylinders and the curvature at their ends were identical. Finally in both chapters the cylinders rested on their side at the same height in relation to the tabletop. For the same purpose of Chapter 5, both ends of the cylinder, by which it had to be pinched, were curved to amplify the effects of friction. As explained in Chapter 3, on a curved surface a grasp generates a unique normal reaction force direction at every contact point. The cone of friction induced by the surface friction defines the surface area onto which a grip force can be applied for a stable pinch grip. The decrease in surface's coefficient of friction reduces this area, amplifying the difficulty to achieve a stable grip. To cover a large hand aperture scope, the range of cylinders' lengths tested went from 54 mm to 151 mm.

A force transducer (Dytran 1053V1) was fixed onto a support by a clip holding the axis of the load transducer 55 mm above tabletop. The support was itself fixed on the table, stopping any possible movement of the entire apparatus. The different widths were achieved by screwing cylinders of different lengths on each side of the force transducer. The force transducer had a 10-32 tapped hole 4.445 mm deep on both side. Directly screwing caps of different lengths on the force transducer through such small threads would have made the whole operation and apparatus delicate and fragile. Moreover, repetitive screwing and unscrewing directly onto the force transducer could have damaged it. This is the reason why flat-ends cylinders ('extension cylinders') were screwed on both sides of the force transducer, and never moved throughout the experiment. Finally, rounded-end cylinders of different lengths (here and thereafter called 'caps') were screwed onto the extension cylinders through their 6 mm deep M10 hole. The caps had a thread at one end, which was screwed in the extension cylinders, and a 25 mm radius rounded-end on the opposite side. For every pinch test the two caps fixed on each side of the force transducer were of identical lengths. The resulting apparatus is sketched in Figure 6.1.

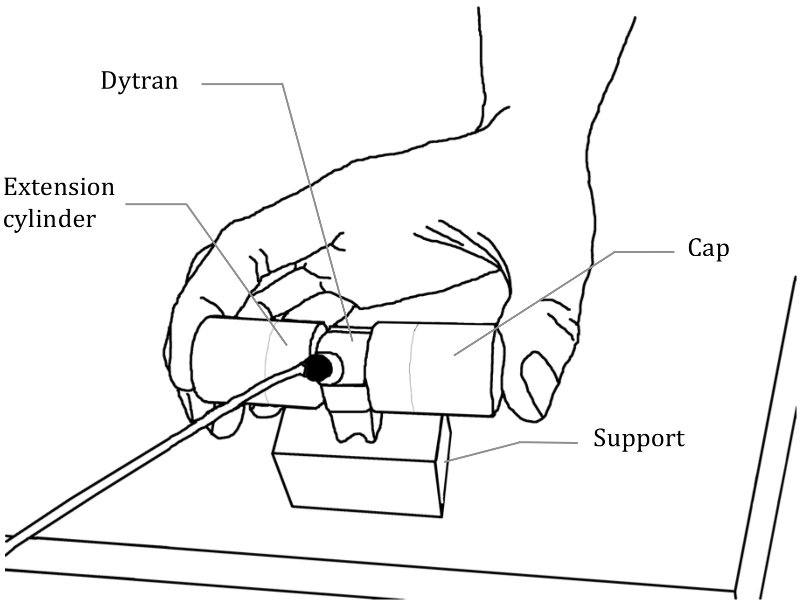


Figure 6.1 Model of the entire apparatus to be pinched grip by its rounded ends, with the Dytran force transducer screwed onto its support, and between the two extension cylinders and cylinder caps.

The lengths of the caps went from 5 to 55 mm with a 5 mm increment, resulting in 11 apparatus sizes with an overall length including caps, extension cylinders and force transducer (Table 6.1). All the cylinders had a 25 mm radius, 25 mm end radii, and were made of Nylon.

Table 6.1 Lengths of cap cylinders fixed on both sides of the force transducer and their corresponding apparatus overall length to be pinched.

Overall object lengths (mm)	54	64	71	81	91	101	111	121	131	141	151
Cap cylinder lengths (mm)	5	10	15	20	25	30	35	40	45	50	55

Due to manufacturing constraints (the objects were too small to be held by the threading machine), the caps of 5 and 10 mm could not have been threaded all the way through. These caps could therefore not be completely screwed onto the extension cylinders creating a gap between the extension cylinders and the caps. This extended the two smallest cylinders by 3 mm, resulting in overall object lengths of 54 and 64 mm instead of what should have been 51 and 61 mm (Table 6.1). The Dytran was attached to a 4120C charge amplifier generating an output of 5V scale AC coupled signal proportional to the force in Newton (N). In the case of the 1053V1 Dytran force transducer, 5 V is equivalent to 44.48 N. The Dytran force transducer was connected to a National Instrument DAQ BNC-2110, and a Labview VI collected the data.

To determine the effect of surface friction on the maximal pinch grip force as the grip aperture varies, a second set of cylinders, identical for every length was used. Petroleum jelly (Vaseline®, Unilever) was frequently applied with a soft-bristled brush to the rounded ends of all the cylinders of this second set throughout every session (application was repeated on alternate trials). This resulted in two sets for all widths with two distinct friction conditions: the 'as machined' objects (high friction) and the 'slippery' objects (low friction). Both sets had as machined Nylon smooth surfaces, but the second set surface's friction was lowered by the Vaseline.

Procedure

Many studies have evaluated people's strength capacities by measuring their maximal grip force. Yet in day-to-day life people rarely use their maximal strength, especially when handling kitchen utensils. During this research, grip force capacity was defined as the amount of force one can produce over a short period of time. Such measure not only reveals the quantity of force one can produce but also their reactiveness. The interest was not in people's absolute maximum force but rather in their force capacity over a short and rapid pinch, which is more representative of a real life grasp situation. As a result subjects were instructed to reach for the object, give it a "hard pinch" between their thumb and index finger for approximately one or two seconds, and release without dwelling on it trying to reach their maximal grip force. Subjects sat in an ordinary chair with their right upper arm parallel to their trunk, and with their elbow flexed at approximately 90˚ and forearm extending anteriorly horizontally rested on a table. The object could not be moved; participants were therefore to concentrate on their grip force application and timing, rather than on trying to secure their grip. The whole sequence from the "go" indication of the researcher to the moment the object was released is here and after considered as a *trial*.

Each of the 22 object combinations (11 widths x 2 surface frictions) was submitted to three successive pinch grips by each participant. Every width combination was randomly presented to the subject within a friction condition, and both friction conditions series were randomly ordered from one subject to the next. Young adults sessions were organised in two parts: in one part they performed all the tests with their hand free, and in the other they performed all the tests wearing CISG. Both hand condition groups were randomly presented between subjects. Between each trial subjects were left a few seconds to rest while the force transducer stabilised itself. In addition to that a minimum of 1-minute break was given between each width series to minimize muscle fatigue.

Analysis

The Dytran force transducer recorded the voltage variations of the charge of its condenser, which was then converted into load measurements in Newton. It was used to measure the maximal pinch grip force participants applied on the apparatus during their hard and short precision grip. The average forces over the three trials for the older participants, the younger participants, and the younger participants with CISG were calculated for every width condition. Repeated measures analyses were run to determine the effects of age, object width, and friction. Partial eta squared (η^2) values are reported for statistically significant findings. The data was tested for violations of sphericity and, whether the assumption of sphericity was not met, Greenhouse-Geisser corrections of epsilon (ε) were applied to the degrees of freedom. The variability of the reported measurements is graphically represented as error bars in this chapter. They are a representation of the standard error of the mean (SEM), which is calculated with the sample standard deviation divided by the square root of the sample size. The analysis was extended further to compare the grip force capacity differences between genders.

6.1.2 Results and Discussion

The Stationary Experiment tested the pinch grip force capacities of different population samples to determine the relative effects of ageing and low dexterity. The results obtained from the young adults wearing CISG during the Stationary Experiment gave indications on the consequence of low finger dexterity on grip force capacities. This part of the study is based on the data collected from the young and older adults who took part in the Stationary Experiment. In order to determine the differences due to age and also due to lower dexterity, the analysis classified the subjects in three population samples: the older adults, the free-handed young adults, and the gloved young adults (data collected when the young adults were wearing the CISG).

All participants managed to pinch the objects for most object widths. The largest object could not be pinched by two of the free-handed young participants in the high and low friction conditions; a third subject could not squeeze it either in the low friction condition but managed it in the high friction condition. The widest object was too large for people to get around it and secure a stable grip. Participants were not just far from reaching the two apexes of both rounded ends of the cylinder with any of their two digits, they barely could touch any part of the rounded ends. The two fully extended digits could hardly generate two opposing forces, and the ability to squeeze the object was thus greatly reduced. With the coefficient of friction of the object surface significantly lowered by the Vaseline, the frictional forces were not sufficient to avoid slippage for such width. In the older people cohort four subjects could not squeeze the widest object in the low friction condition of which two could not do it either in the high friction condition. One of the two could also not squeeze the second largest object in both conditions. The young subjects who failed to pinch the largest object in the low friction condition also failed the high and low friction conditions when wearing CISG. These cases thus reduced the sample sizes for the widest and second widest objects in both conditions. This evidently has an effect on the averaged pinch grip force capacities recorded for those objects, but it has little effect on the analysis. As a matter of fact the widest objects were designed to push people to the limits of their handgrip aperture, and therefore cover the widest pinch grip aperture range possible. The widest objects were expected to be too wide for some; those failed trials confirm that maximal graspable widths were tested.

The objectives of the results from the Stationary Experiment are to reveal the evolution of people's grip force capacities with grip aperture and surface friction, and to observe the differences between generations as well as the effect of low dexterity. There was a significant main effect of surface friction on participants' pinch grip force ($F(1,23) = 171.142$, $p < 0.01$, $\eta^2 = 0.836$). The force applied on low friction objects was always smaller than the one applied on high friction objects for identical cylinder lengths. The width of the object to be pinched had a statistically significant effect on the pinch grip force as well ($F(10,230) = 31.696$, $p < 0.01$, $\eta^2 = 0.579$, $\varepsilon = 0.158$; Figure 6.2). As the cylinders' length started to reach the maximal pinch grip aperture of people's hand the force they applied significantly decreased. Additionally there was a significant effect of hand size ($F(9,16) = 7.821$, $p < 0.01$, $\eta^2 = 0.815$), and maximal pinch grip aperture ($F(9,16) = 3.294$, $p < 0.05$, $\eta^2 = 0.650$) on the maximal pinch force people applied. In general people with larger hands could apply a larger force throughout all widths.

Across all trials and participants, older people did not apply a significantly different pinch grip force than young adults (not wearing a CISG) ($F(1,15) = 0.029$, $p = 0.867$). There were no significant differences between the two cohorts separately in the high ($F(1,18) = 0.217$, $p = 0.647$) and low friction conditions ($F(1,15) = 0.08$, $p = 0.929$). Cambridge Impairment Simulator Gloves had no significant effect on the maximal stationary pinch grip force of young adults ($F(1,16) = 0.037$, $p = 0.849$), whether the trials were done on the high friction ($F(1,17) = 0.014$, $p = 0.909$) or the low friction surfaces ($F(1,16) = 0.179$, $p = 678$). Age and gloves did not have any significant effect on subjects' pinch grip force capacity, therefore it is only logical that no differences between the maximal pinch grip force of older adults and of young adults wearing a CISG were found ($F(1,15) = 0.149$, $p = 0.705$).

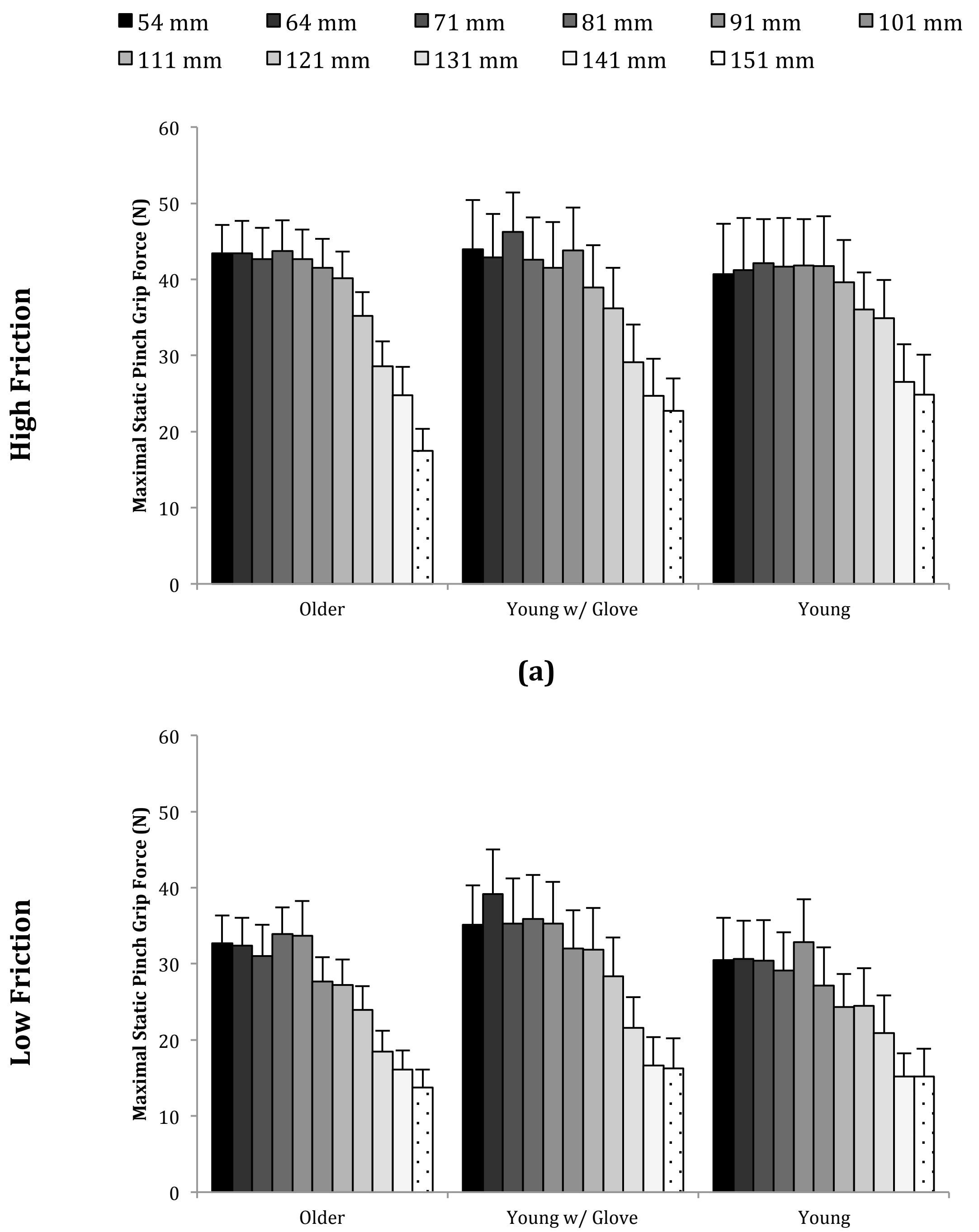


Figure 6.2 Evolution of pinch grip force capacities with object width for older and younger adults with and without CISG in (a) the high and (b) low friction conditions.

Normalised Data

To complete the information given by the data and graphs above, grip force was normalised and studied while removing the anthropometric data, because hand size affects grip force. As could have been predicted, people with larger hands could apply greater force on wide objects, but interestingly they could also apply more force on the smallest objects. Removing the anthropometric data is achieved by reporting the pinch grip force against the ratio of object width (D) over hand size (l) (Freund et al., 2002). Furthermore, individual pinch grip forces were normalised so not to compare individuals in terms of raw force, but rather in terms of individual capabilities. This normalisation consisted in expressing, for every individual, the averaged measured grip force for every object (f) as a proportion of the peak grip force that subject reached over the entire range of objects (f_{max}) (Freund et al., 2002). A repeated measures analysis demonstrated that in both friction conditions f/f_{max} was significantly affected by the ratio of object size over hand size ($F(97,31) = 1.966$, $p < 0.05$, $\eta^2 = 0.860$; Figure 6.3). To examine the evolution of the relative grip force capacities, the average f/f_{max} is plotted in Figure 6.3 on an Object/Hand size axis, where hand size is the average hand size for the corresponding group. The process of reporting object size over body scale has already been illustrated by Warren and his work on body scale affordances (Warren, 1984).

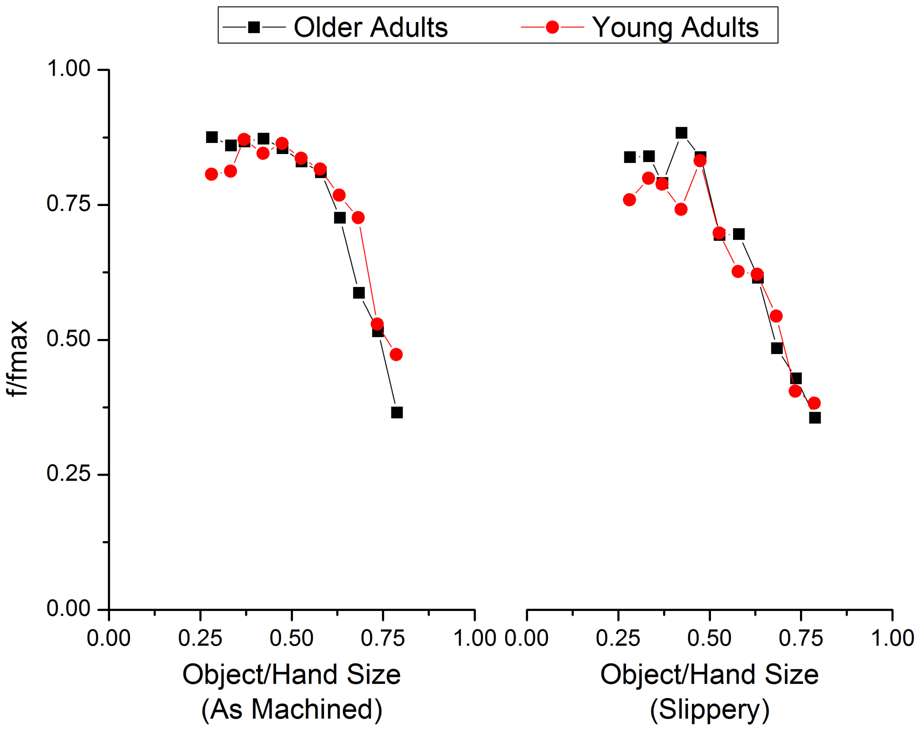
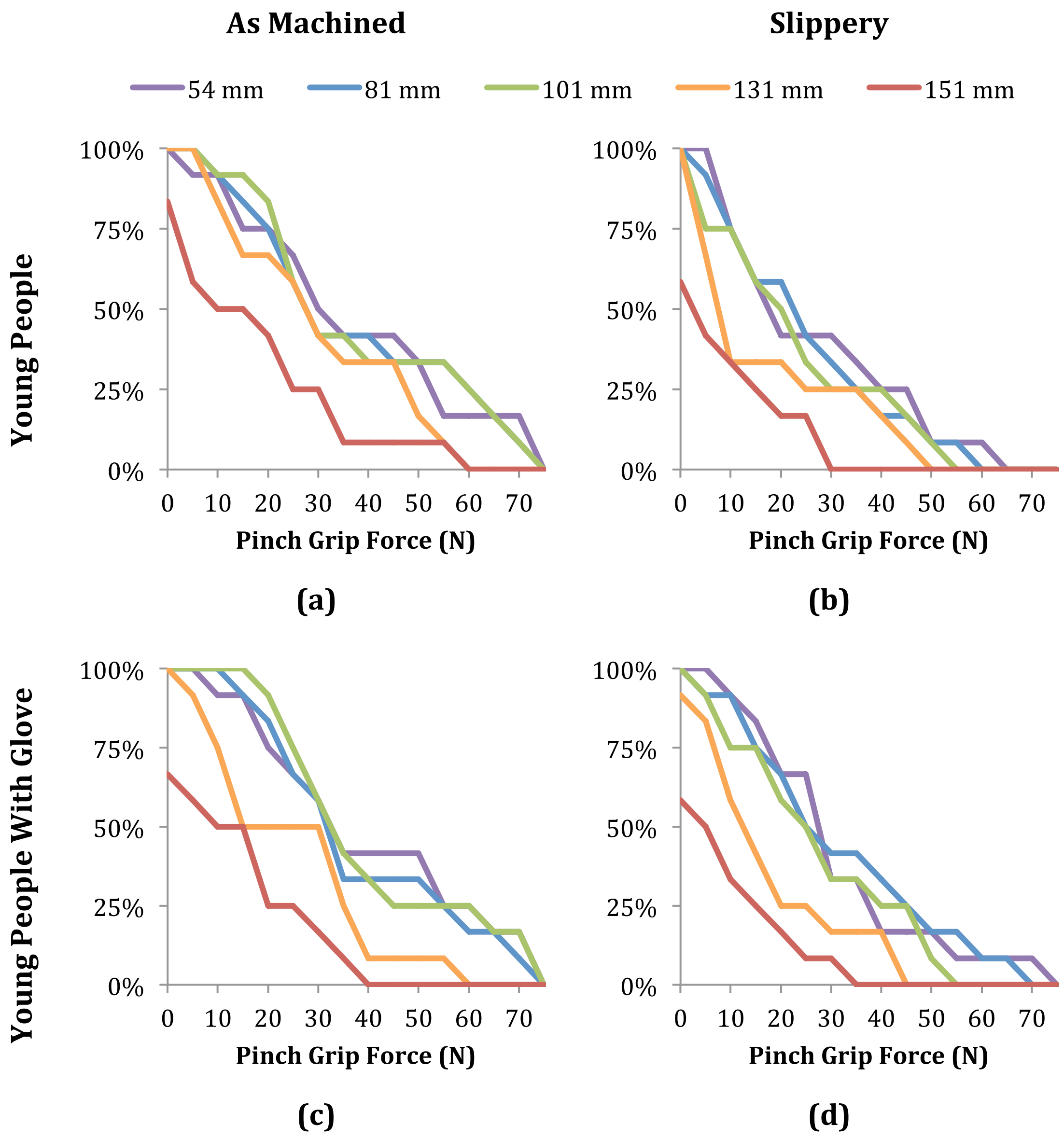


Figure 6.3 Average grip force capacities over peak capacities (f/fmax) as a function of object width over hand size for each group and in both friction conditions.

For all participant groups and for both surfaces' coefficients of friction, it can be seen that both age groups' normalised capacities evolve similarly regardless of the surface friction. From Figure 6.3, it appears that, when the object width is less than 40% of people's hand size in the low friction condition or 60% in the high friction condition, then people's grip force capacities are at an approximately constant and stable highest. However, once the object gets wider (past that ratio) people's grip force capacities drastically drop.

Reverse Cumulative Frequency

It has been demonstrated that generally as the object got wider participants applied less and less force. A reverse cumulative frequency analysis showed the proportion of the population for each population group who could apply a given force on the apparatus for selected widths (Figure 6.4) in both surface friction conditions. For clarify only a few widths were selected to be represented in the following figure. The 54 mm and 151 mm widths were selected for being respectively the smallest and largest ones tested. The 101 mm width sits at the end of the grip force plateau region and halfway between the two extreme widths. The 81 mm width is well inside the force plateau region, and the 131 mm one is in between the 101 and 151 mm widths. They were both selected for the observation of the progressive evolution of the reverse cumulative frequency with width. The three smallest widths represented were also the widths selected for the Perturbation Experiment.



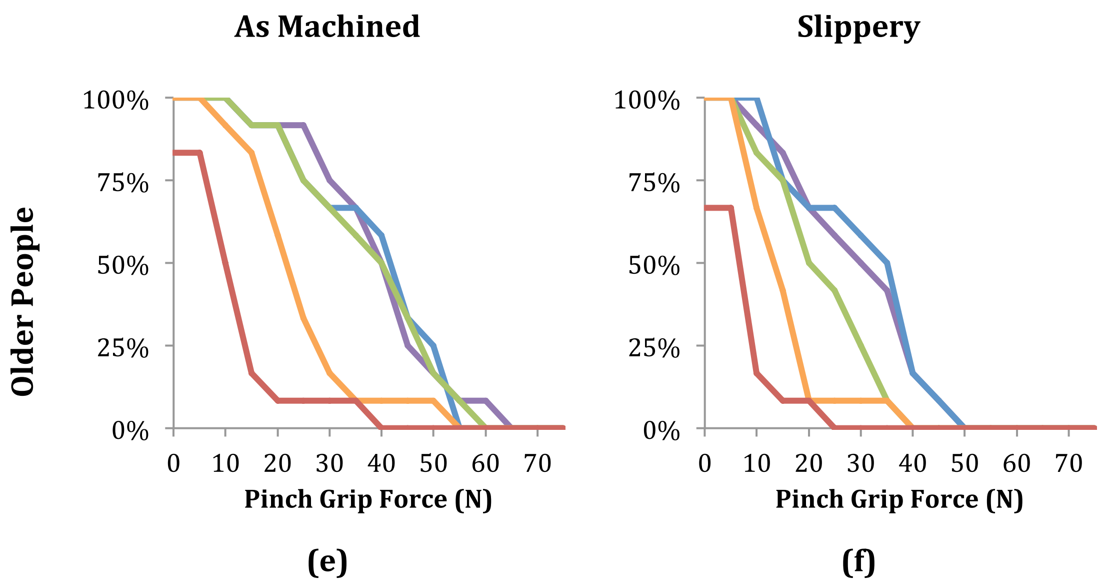


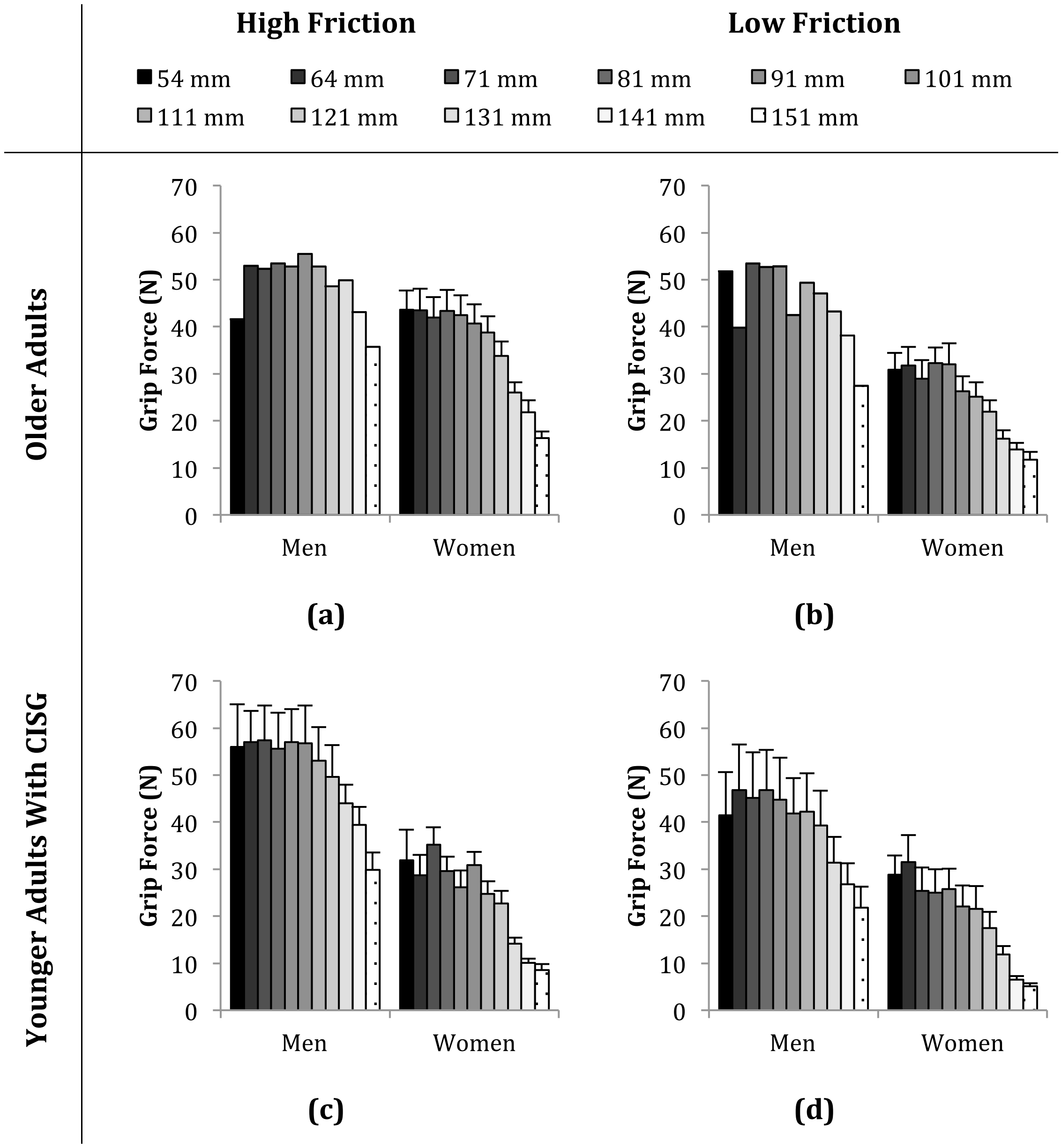
Figure 6.4 Reverse cumulative frequency plots of the percentage of participants reaching specific pinch grip forces for each object width in the high friction condition for (a) young, (c) young with CISG, and (e) older subjects; and in the low friction condition for (b) young, (d) young with CISG, and (f) older subjects.

It can be seen that the percentage of participants who could apply a given force decreases, for the most part, almost linearly in both friction conditions. The largest object widths however have a more sudden and sequential decrease. Their decrease starts earlier and is also steeper than the rest of the widths. The quantity of people who could pinch a given object decreases similarly for all object widths as long as the object is smaller than 10 cm. Then the curves are more and more distinct.

Gender Differences

The older people who agreed to take part in this chapter's study were predominantly women. Only one older man participated whilst the young cohort is evenly distributed between men and women. Men are known to be generally stronger than women, and the imbalanced proportion of participants' gender is therefore likely to skew the results. However no tenable statistical analysis can be run with such a low number of participants per gender and age group. Nevertheless, with that in mind, plotting the male data against the women's one could highlight possible existing differences between the two genders.

Women's averaged grip force capacities are smaller than men's for every width regardless of their age and dexterity (Figure 6.5). The gap between genders is greater in the younger population, certainly due to the fact that the older male data came from only one participant; which explains the inexistence of error bars. The slipperiness seems to cause an overall decrease of 10 N for everybody except for the older man, again probably the results of a too small sample size. It appears that older women always applied a larger grip force than young women.



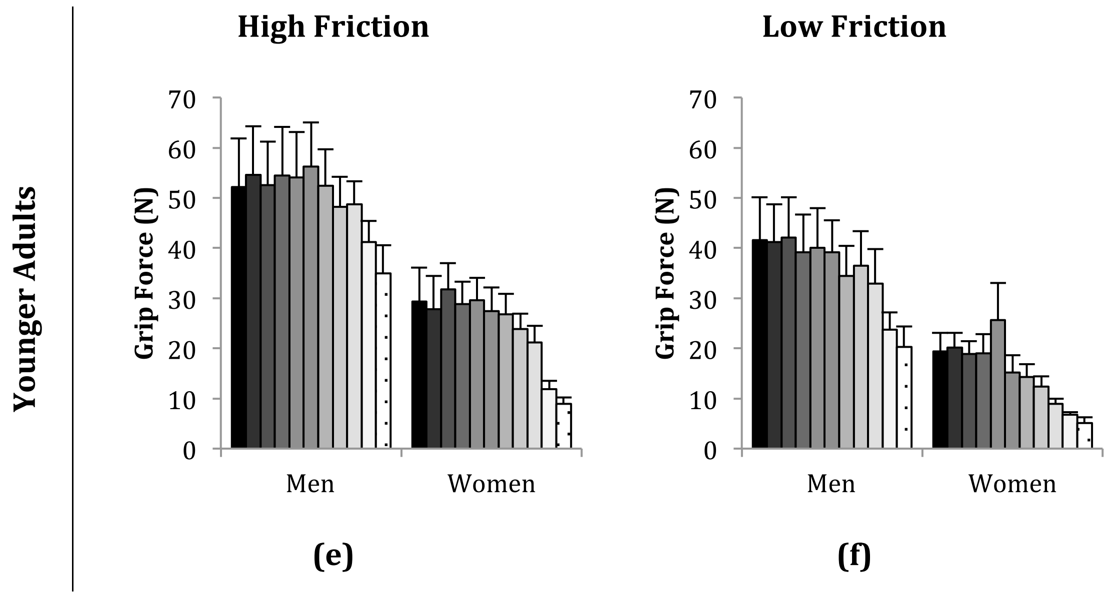


Figure 6.5 Hard pinch grip force evolution with object width for men and women in the high friction condition for (a) older adults, (c) younger adults with CISG, (e) younger adults, and in the low friction condition for (b) older adults, (d) younger adults with CISG, and (f) younger adults.

The Stationary Experiment, by discovering the evolution of pinch force capacities with aperture width, revealed the existence of a zone where people's grip force capacities are at their highest. This zone is defined by the ratio of the object width over the user's hand. The second experiment, the Perturbation Experiment, investigated the behavioural changes people adopt to cope with sudden and unpredictable perturbations in a lifting movement. Similarly to the Stationary Experiment, the Perturbation Experiment aimed at unveiling the effects of object width and friction, and people's age on grip force used to lift objects within the plateau region discovered in the Stationary Experiment.

6.2 The Perturbation Experiment: Pinch Grip Force During Perturbed Lift

6.2.1 Methods

Participants

In the Stationary Experiment, to maximise the perceived effects of CISG, and consequently loss of dexterity, the exact same young subjects ran the tests with and without CISG. Due to the length of each experiment younger participants could not perform both experiments in one single session. Therefore a second group of 12 young adults was recruited to take part in the Perturbation Experiment. This group did not have to be the same as the one of the Stationary Experiment, because the tests between the two experiments were not reflecting the same aspect of a grasp. In these perturbed pinch grip sessions took part a group of 12 young adults (age mean 25.00 years, age range 21 – 29 years; seven females, 11 reported right hand preference), and a group of 12 older adults. The exact same cohort of older adults took part in both the Stationary and the Perturbation Experiment in one single session. Sessions for young and older adults lasted approximately one hour. All participants had normal or corrected-to-normal vision and no history of neurological deficit or hand deficiency such as arthritis. MGA was measured for each individual (young adults group: MGA mean 14.90 cm, and range 12.0 – 17.5 cm; older adults group: MGA mean 13.26 cm, and range 11.0 – 15.5 cm). All subjects provided informed consent prior to inclusion in the study, which had been approved by the University Ethics Committee, and received £5.00 for taking part in the study. They were randomly selected from a list of contacts, and recruited by email or phone. They were completely naïve with regard to the present study purpose.

Apparatus

In this second experiment the same apparatus as in the Stationary Experiment was used with the addition of a few modifications. For this series of tests the object had to be grasped and picked up. The support was therefore no longer fixed to the table; metal plates were screwed underneath the support so that it could rest balanced above a hole cut in the table. For every lift a perturbation was inflected in the form of a sudden stop in the object course. Attached to the floor and passing through the table hole, threads of varying lengths were hooked underneath the support so that past a certain height the tension of the thread would stop participants in their vertical lifting motion. There were three different lengths of thread that could be hooked underneath the apparatus, allowing respectively lifts of approximately 5, 10, and 15 cm above the tabletop. Johansson and Westling (Johansson, R.S. & Westling, G., 1988) suggested that subjects' grip force was adjusted on the basis of previous lift conditions. Testing different lift height limitations prohibited subjects from anticipating when they would be stopped, which would have been likely to influence their grip force.

Three cylinder lengths of the 11 used in the first experiment were selected. These were first the smallest width achievable on this apparatus (54 mm with a 5 mm cap), then a medium width (81 mm), and finally a large width (101 mm). These three lengths were selected as they appear, from the Stationary Experiment's results, to cover the whole plateau region where people's force capacity is at its maximal. Past the 101 mm width grip force capacities dropped dramatically, while the 81 mm width sits well within the plateau region, approximately halfway between the 54 mm and 101 mm widths. Throughout all trials the apparatus weight had to remain constant, as a larger weight would have forced a higher lifting force from the participant. Therefore small weights were screwed onto the support or removed on alternate width trials so that the small, medium, and large apparatus all weighted a total of 250 g.

In addition to the Dytran force transducer, a load cell was incremented on the apparatus to accurately measure the slip force. The load cell was a Honeywell® Micro Switch Force Sensor FSG-15N1A providing an inherently stable mV output over a 1500 gram force range. The Honeywell had a lower force capacity than the Dytran but offered a more precise and reliable reading, especially with constant force application and subtle variations, such as what can be observed when grip force is slowly reduced. A cut was extruded from one end of all the three cylinders in order to slide in the Honeywell so that only the sensor tip would come out at the apex of one of the apparatus rounded ends (Figure 6.6). The Honeywell was connected to the same DAQ as the Dytran.

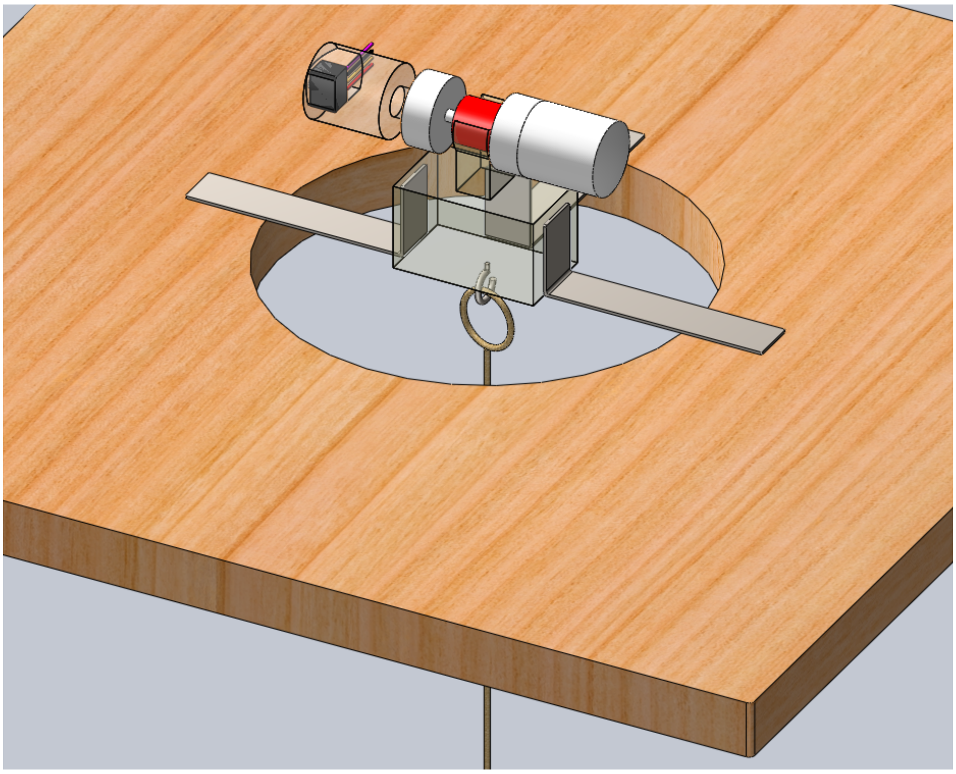


Figure 6.6 3D sketch of the apparatus mounted with the Dytran force transducer in the centre (in red) and the Honeywell load cell (in black) at one end.

Procedure

This lifting task required participants to reach and pinch grip the apparatus similarly to the Stationary Experiment, and then lift it up vertically until stopped. Participants were left to perform a few unperturbed dummy trials, during which the researcher observed their pace. They were instructed to use similar pace during all of the trials. The apparatus was to be lifted to a 50 cm height (a mark showed the reference). However subjects were informed that at some point in their lifting motion prior to reaching the limit height they would be stopped by the tension of the thread hooked underneath the apparatus. Nevertheless the instructions were not to be too cautious and slow waiting for the thread to tighten, but rather to use the same sort of pace they used in the dummy trials. They were informed that the intention was to observe the disturbance the sudden stop would have on their handling during a normal daily pick up of a random product. Once the whole procedure was explained participants were left again to try a few dummy lifts with one thread hooked underneath the object. During the experiment a trial was considered as failed and repeated if the researcher judged the lift as too cautious, by being significantly slower than the pace used in the dummy trials. If the object slipped off the participants' fingers unintentionally then the trial was considered as a 'drop'. The number of unintentional drops was noted for each participant. Once they had reached the height limit and managed to keep hold of the object, participants were asked to slowly release the object by opening their grip until it slipped out of their grasp. One second passed between the moment people's motion was stopped and the moment they started releasing their grip. The slip force was recorded via the Honeywell at the instant the object fell off participants' fingers.

There were three different apparatus sizes and two object surface coefficients of friction resulting in six different combinations. For the lifting measures, within each friction condition group the three different widths were randomly presented to the participants. The presentation order for friction condition groups was randomised between subjects. After every trial the length of the thread was randomly changed between the three available lengths. Subjects were never aware of which length of thread was attached to the apparatus; even in case of trial failure or drops the thread condition was changed.

Young adults performed nine successive lifts for every width and friction condition, making sessions for the Perturbation Experiment last one hour. It was later noticed that nine repetitions would be likely to cause fatigue in digits and boredom for an older population, while not generating a significant improvement compared to three repetitions. When a test is too long and fatiguing, people are likely to lose interest and their performances to be affected. Therefore the older participants performed only three consecutive lifts in the Perturbation Experiment. It is for that reason and the fact that there was no rationale to have them run CISG tests that older people could run both experiments (i.e., the Stationary and the Perturbation Experiment) in one single session of one hour. In the analysis, only the data from the first three lifts per condition of the younger cohort were retained.

Because the Stationary Experiment required people to perform a hard pinch and therefore use a large amount of force it caused more finger grip force fatigue. In order for this not to affect the reach-to-grasp-and-lift actions of the Perturbation Experiment, older people, who in a single session had to perform both experiments, always performed the Perturbation Experiment before the Stationary Experiment. They were given a few minutes break in between each experiment. Before starting any lifting trials subjects were asked to apply a hard pinch on the Dytran, and on the three apparatus widths (i.e., 54, 81, 101 mm) in both friction conditions, in similar conditions to what people did in the Stationary Experiment. They only performed one single pinch per object condition; the force was recorded by the Dytran as the Honeywell was not implemented for those tests. These measurements were to evaluate people's pinch grip force capacities, allowing comparison with the young cohort of the Stationary Experiment. During the Perturbation Experiment, older people were not asked to pinch the three apparatus width before starting the lifting task, because they were about to record those readings in the Stationary Experiment later in the session. However, during the Perturbation Experiment they recorded a force reading of a maximal pinch grip directly on the Dytran similarly to young adults.

Analysis

The Dytran force transducer was used to read the maximal pinch grip force reached by participants as they lifted the apparatus to prevent the object from slipping across the entire lifting motion, referred to as the 'Peak Force'. The statistical analysis of the slip forces was based on the readings the Honeywell gave when participants let the apparatus slip from their grip. The Honeywell was preferred over the Dytran for the slip force measurements, because of the latter's discharge during low load variations, occurring when people are slowly releasing their grip. The time at which the object was dropped and fell coincided with the instant the derivative of the Honeywell's force readings was at its lowest. The slip force, minimal force one must apply in order to avoid the object from slipping out of hand, corresponded to the force recorded by the Honeywell at that precise time. As the Honeywell's readings were noisy the derivative was calculated from the load cell's reading to which an Inverse Chebyshev filter was applied to smoothen the signal. The inverse Chebyshev filter has a step response similar to Butterworth, but also minimises the error over the range of the filter. It therefore generates a smooth and gradual oscillation with no sudden variations, which could have generated low derivative calculations not corresponding to the object drop instant.

Similarly to the Stationary Experiment, a repeated measures analysis was run on the median data of the first three successful lifts completed by each individual of the two population samples. As the values could suffer high fluctuation and therefore contain outliers, the median was opted over the mean. It meant to identify possible effects of surface's coefficient of friction, object width, and age on people's slip force, peak force, and the proportion of slip force over peak force (normalised slip force).

6.2.2 Results and Discussion

Between the Stationary Experiment (SE) and the Perturbation Experiment (PE), a total of three population groups of 12 subjects were recruited. Firstly, pinch grip force capacities of every group had to be known in order to identify stronger and weaker groups. For every group, people's pinch grip force capacities were measured for the 54 mm, 81 mm, and 101 mm widths in both friction conditions. The people who participated in the Perturbation Experiment also recorded a single hard pinch directly on the Dytran. According to each experiment's procedure, the young group who took part in the Stationary Experiment and the older group (who took part in both experiments) recorded three readings while the young group who only took part in the Perturbation Experiment recorded one. Therefore the average grip force capacities for each cohort over the first (or only) individual hard pinch of the twelve participants is represented in Figure 6.7, for every one of the three widths and for both friction conditions, together with the Dytran hard pinch average readings.

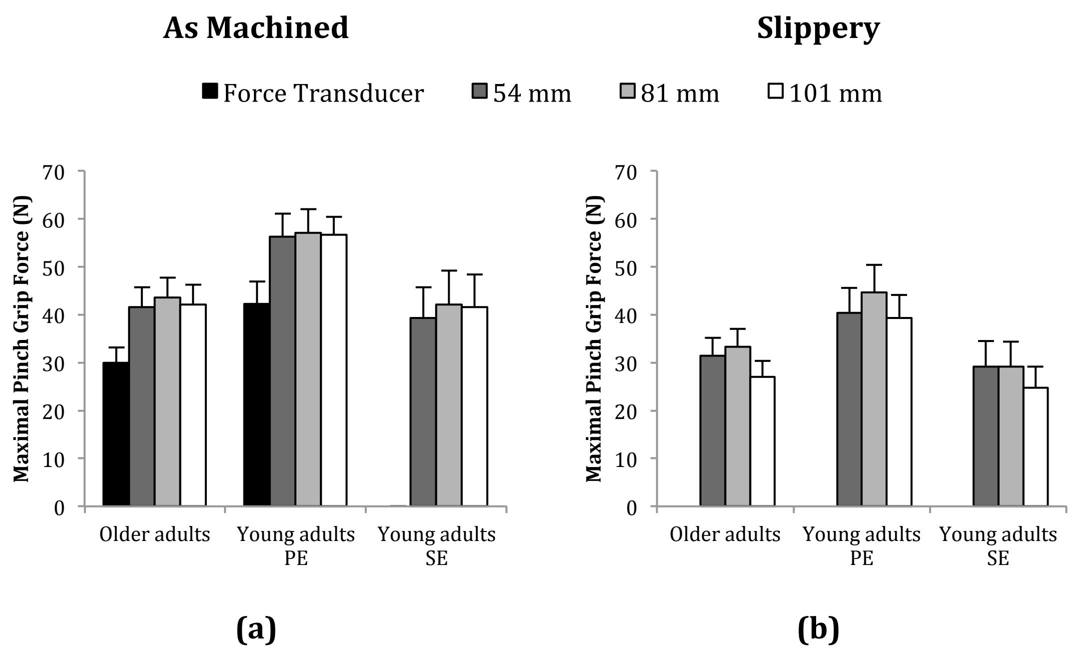


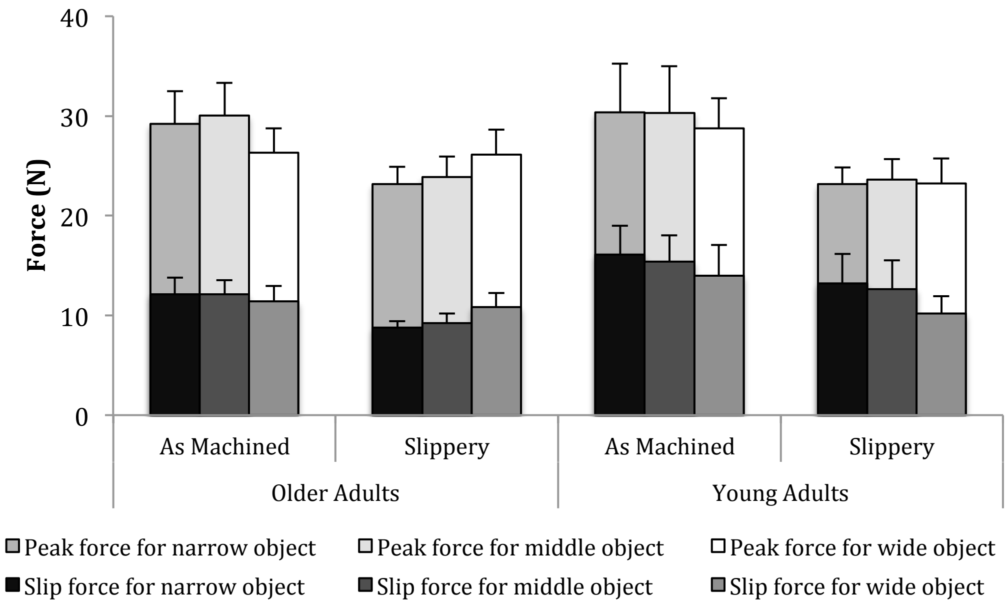
Figure 6.7 Maximal stationary pinch grip force of the first successful hard pinch for the three participant groups in (a) the high friction and (b) the low friction condition for the force transducer and the three widths utilized in the Perturbation Experiment.

The Perturbation Experiment measured the pinch grip force used by people to cope with a sudden and unpredictable perturbation in their lifting motion, as well as its proportion compared to the minimal force required to hold the object stable in the air. It also evaluated the effect of age on the latter two forces. This part of the study is based on the data collected from the young and older adults who took part in the Perturbation Experiment. Out of all the 12 young participants one could not pick up the widest object in the low friction condition, and five out of twelve older people could not do it either, of which two did not manage it in the high friction condition. This high proportion of failure for the widest object demonstrated the difficulty that a too large width can generate, unfortunately the lack of measurements for this width condition forced its removal from the statistical analysis. Therefore the repeated measures analysis was run on two friction conditions, two width conditions, and two age conditions. However, the widest width data was kept for graphical observations.

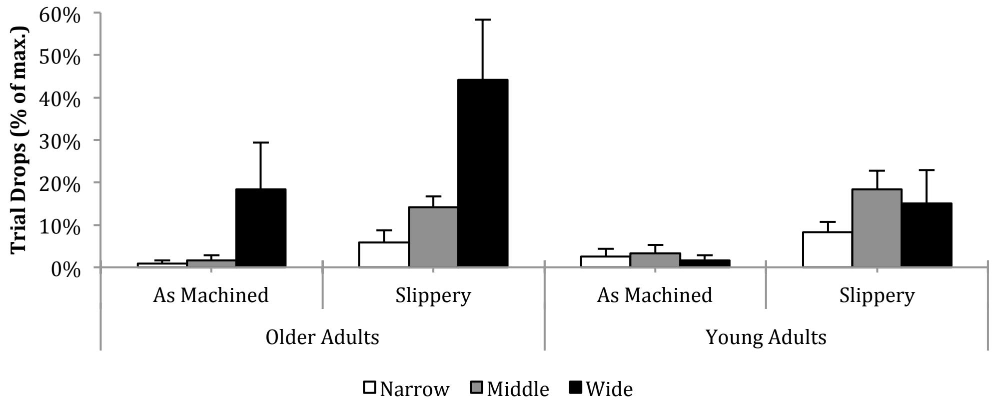
The width of the object was found to have no significant effect on neither Peak Force ($F_{peak}(1,22) = 0.184$, $p_{peak} = 0.672$), nor Slip Force ($F_{slip}(1,22) = 0.106$, $p_{slip} = 0.748$), nor normalised Slip Force ($F_{n\_slip}(1,22) = 0.758$, $p_{n\_slip} = 0.393$, $\varepsilon = 0.744$). However it had a significant effect on the proportion of drops ($F(2,44) = 4.983$, $p < 0.05$, $\varepsilon = 0.562$, $\eta^2 = 0.185$; Figure 6.8(b)). Wide objects are more difficult to grasp and are therefore the cause for more drops.

The friction of the object surface had a significant effect on Peak Force ($F(1,22) = 24.112$, $p < 0.01$, $\eta^2 = 0.523$; Figure 6.8(a)), with lower friction both age groups applied less force. This is the opposite of what was expected, but it is in correlation with the lower forces observed on lower friction objects in the Stationary Experiment. On average peak force is 6 N higher in the high friction condition for every width condition and every age, with the exception of the widest object for older adults. The widest object, suffering lack of participant success, observed an average peak force 2 N higher in the low friction condition, resulting from high scores on wide low friction objects for the older adults. As expected, because low friction facilitates slippage, surface friction had a significant effect on Slip Force ($F(1,22) = 6.823$, $p < 0.05$, $\eta^2 = 0.237$; Figure 6.8(a)). Normalised Slip Force ($F(1,22) = 0.010$, $p = 0.922$) was not significantly affected by friction. Low friction objects were more difficult to grasp, which impacted on the proportion of drop trials ($F(1,22) = 26.822$, $p < 0.01$, $\eta^2 = 0.549$; Figure 6.8(b))

Finally, age was influencing neither Peak Force ($F(1,22) = 0.003$, $p = 0.956$), nor Slip Force ($F(1,22) = 1.936$, $p = 0.178$), but normalised Slip Force ($F(1,22) = 12.443$, $p < 0.01$, $\eta^2 = 0.361$). The older people did not appear to have weaker grasps since they were applying similar pinch grip forces to their younger counterparts across all trials. Proportionally to their individual peak grip force the difference between peak and slip forces is smaller for younger adults than for older adults. This indicates the use of a larger force safety margin by the older people, reflecting a more cautious yet more demanding grasp, in line with the literature. However in terms of dropped attempts, there was a significant interaction between object width and age ($F(2,44) = 4.339$, $p < 0.05$, $\eta^2 = 0.165$; Figure 6.8(b)) proving that older people struggled more around wider objects. There was however no effect of age on the proportion of drops ($F(1,22) = 2.028$, $p = 0.168$), reflecting that except for the widest object older people did not significantly find more difficulty in the lifting task than did young people.



(a)



(b)

Figure 6.8 (a) The average peak pinch grip force recorded during the entire lifting movement and slip force recorded at drop over the first three successful lifts. (b) Number of unintentional drops before three successful lifts were recorded.

As seen in Figure 6.8(a), peak grip force was on average 2.5 times greater than slip force for older people and 2 times greater for young people, across all trials. The safety margins (force difference between peak force and slip force) thus created here represent approximately between 50% and 60% of the peak force applied on the object to cope with the sudden stop. This is largely superior to what can be found in literature. This difference is hypothesised to be due to the high reaction force people used to cope with the perturbation. An example of a grip force evolution for a trial from one subject and its evolution as the object is stopped and released is represented in Figure 6.9.

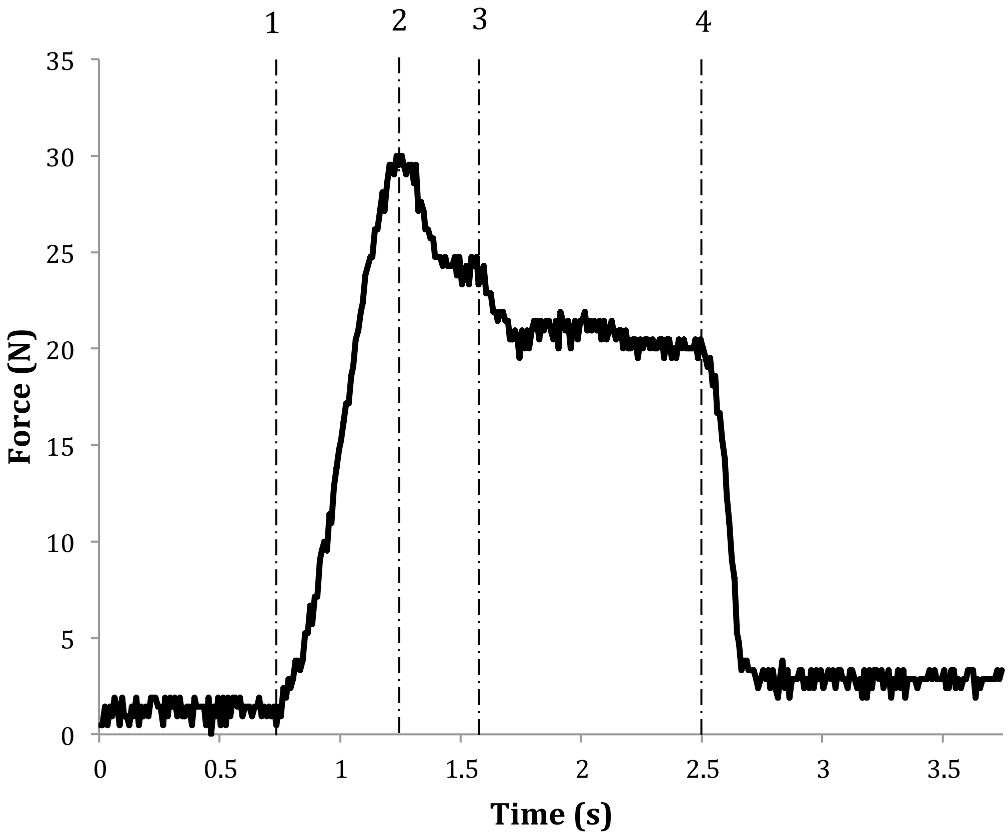


Figure 6.9 Grip force of a perturbed lifting movement of a subject. 1, the subject's fingers get in contact with the object surface. 2, the object is stopped by the tension in the thread. 3, the object begins to be slowly released by the participant. 4, the object slips out of grasp.

6.3 Discussion

In a precision grip the thumb and index are both applying a given force on the object surface at each contact point. Both digits' grip forces have a component normal to the object's surface, and one tangential to the object's surface; both fluctuate in parallel. The stability of the contact is only dependent on the angle of the grip at the point of contact, and on the coefficient of friction between the skin and object surface. In the case where both digits cannot apply a grip force perfectly normal to the object surface and in perfect alignment with one another, then they generate a thrust force component that is pulling the object out of grasp (Fearing, 1986). However as long as there is no slippage between the fingers and the object that force does not influence the stability of the grasp, Nonetheless, the angle of the grip force can increase this thrust force, and if the grip force angle grows to be larger than the cone of friction semi-angle then slippage occurs.

In the present case the geometry of the apparatus is a simple cylinder extending from one fingertip to the other. A vector force is created between the two fingertips when the cylinder is squeezed at both ends. The two digits generate a force at their contact point at both respective ends of the cylinder. In a stable pinch grip, these two grip forces are collinear, of equal magnitude, and opposite direction. For no thrust force to be created both digits must apply a grip force at each apex of the two rounded ends of the apparatus. This configuration is more easily achievable on small width cylinders, but becomes impossible past a certain width. The thrust force is counteracted by frictional forces, therefore a slippery object is more likely to be launched out of grip. The width and friction of a tool to be handled have thus a tremendous role to play in the stability of a pinch grip.

During the Stationary Experiment the object was fixed to a table and could not to be lifted or handled. Even though digits could still slip off the object, it could not be pushed out of grasp, be knocked over, or move as participants tried to position their fingers around it. Thanks to these conditions participants could pinch larger objects than they could have lifted, because the task required far less precision. Consequently few failures were observed, since the stationary task simply consisted in being capable of opening a big enough aperture to apply a force at both ends of the apparatus. Nevertheless, even if the task was less demanding than a lifting task would have been, people's fingers could still slip off the object. Participants had therefore to be more cautious on low friction objects, a behaviour reflected by an approximate 10 N lower force on low friction objects than on identical high friction objects. This gap seems to be constant regardless of the length of the cylinders, and consequently the required hand aperture. In accordance with Enders and Seo's findings (Enders & Seo, 2011), three reasons are postulated to provoke lower grip force on slippery objects. Firstly, the cone of friction, being larger with high friction objects, allows for a given normal grip force larger tangential forces. This component can therefore be greater on high friction surfaces, thus contributing to higher overall grip forces. Secondly, a larger cone of friction permits a wider range of pinch grip force direction, leading to less precision and accurate muscle coordination required, allowing the user to apply greater forces (Engel et al., 2010). Finally, due to a higher risk of slippage between object and skin, low friction gives the sensation of a less secure grip. People apply less grip force on low friction objects because the task is more difficult, requires more care, and transmits a feeling of instability.

Corroborating the theory on grasp, it was observed that the coefficient of friction of the object's surface influenced people's pinch grip force capacities. However, it is not the only object's characteristic, which affect these capacities. Indeed the size of the object, and therefore the size of pinch grip aperture, also has a significant influence on maximal pinch grip force. As a matter of fact the principal goal of the Stationary Experiment was to reveal the evolution of people's grip force capacities with pinch grip aperture across different ages.

This effect of object width on grip force capacities had been predicted. Firstly, grip span has to be increased for wider objects, reducing the number of possible finger arrangements. This effect is amplified by the curved surfaces, by which the object has to be pinched, which further reduce the grip force magnitude and direction patterns. Secondly, extensive research has shown that grip force varies with grip span and handle diameter (Edgren et al., 2004; Freund et al., 2002; Grant et al., 1992; Kong & Lowe, 2005). Finally, the width of the object to be pinched requires a certain grip span, which changes the biomechanical system of the hand and fingers. The joint angles and the muscle lengths change to adjust grip aperture to the object width. These changes greatly influence hand posture, and consequently grip force (Buchholz & Armstrong, 1992).

Both the raw data and the normalised grip force data were shown to be significantly affected by the object width and object to hand size ratio respectively. Similarly to what Imrhan and Rahman found (Imrhan & Rahman, 1995) grip force plateaus at its highest value in low width values, and is followed by a significant drop in peak pinch force. The normalised grip force capacities have an evolution with object size normalised to the users' hand size similar to the one of the raw grip force capacities with object size. In this force plateau region the object is between a third and half the size of people's hand, the object is thus significantly smaller than users' hand size. Regardless of people's age, as the ratio increases past 60% in high friction conditions or 40% in low friction conditions, then normalised grip force drastically drops. According to the results, this decrease appears linear. For every percentage the object width gains over hand size, normalised grip force decreases by approximately 1.5% in the low friction condition for both age groups, and by 1.6 to 2.1% respectively for the young and older cohorts in the high friction condition.

A pinch grip and the applied grip forces ensue from previous experiences (Gordon et al., 1993), the brain's computation of the sensory afferent information on the object (Augurelle et al., 2003; Gordon et al., 1991), and fine coordination of multiple hand muscles (Winges et al., 2008). A predicted grip force is first employed, and if tactile afferent signals trigger information stating an erroneous prediction then adjustments are made. This awareness of the object surface stimulation is obtained by the cutaneous sense based on receptors within the skin. Other sensory receptors, called muscle spindles, are embedded within muscle fibres and generate afferent signals in reaction to changes in muscle length. On reception of these signals the CNS force an automatic response by sending efferent signals that will induce muscle contraction back to the muscle (Hunt & Kuffler, 1951). This kinaesthetic sense gives the user awareness of the static and dynamic body posture (Loomis & Lederman, 1986). Accurate efference allows a precise adaptation of muscle tension and length to the afferent signal generated by the stimulus.

The grip force must overcome the gravitational force through frictional tangential forces in order to lift a given object. In a stable grasp the grip force is larger than the slip force (i.e., minimal force to prevent slip) by a safety margin. Humans never hold an object by solely applying the minimal force required, while it is extremely energy and fatigue efficient it is very hazardous as the object is on the verge of slipping. Furthermore, a safety margin allows time for a reaction to unpredicted load changes, because fast adapting mechanoreceptors can only provoke a motor response within approximately 100 ms (Johansson & Flanagan, 2009). Grip force is modulated in parallel with those variations in load force (Flanagan & Wing, 1993). Grip force is always a precise balance between a sufficient force preventing slip and a low force avoiding finger fatigue and object destruction. The Perturbation Experiment measured peak forces 100-150% greater than slip forces showing that when high loads are expected but not predictable people use a large safety margin during rapid lifts to secure their grip, counteract the sudden addition of inertial forces, and prevent the object from slipping.

The safety margin unexpectedly large is predominantly due to considerably high grip force values. Many aspects of the present research are responsible for such high grip force readings. Firstly, the task was brusque and rapid, and unlike many previous studies grip force was measured at the instant people had to cope with the sudden perturbation, and not while the object was held stable in the air or carried through smooth movements. Previous research data show that grip force peaks during lift and then decreases to settle on the value used to hold the object still in the air. Additionally, people increase their grip force before a perturbation when timing is known. When timing is unpredictable these preparatory actions are absent, and the response triggered by the perturbation is here much stronger (Johansson, R. & Westling, G., 1988). Johansson and Westling observed that for unpredictable perturbations people applied approximately 2.5 times more force than during simple holding of the object in the air. The grip force required to keep hold of an object being pulled out of grasp is potentially high. To prevent the object from slipping during lift people have to grip harder to compensate for the inertial force generated by the lifting acceleration. In the case where a perturbation is fed into the movement then the grip force also has to compensate for the inertial force generated by the perturbation. In the present study, the whole lifting task spread over a short period of time, people did not have the time to adjust their grip. They had to apply a tremendous large grip force to overcome all inertial forces, and make sure the object would not be pulled out of their grip as they hit the height limit. When handling objects with sudden and quick movements, and where drastic perturbations are expected, people apply an exaggeratedly high grip force to secure their grip and be thus able to keep hold of the object no matter what. These results were obtained on solid and hard objects, it would be interesting to see whether people behave similarly when handling fragile objects that can be damaged by a too strong grip.

High grip force values were found in both friction conditions. Similarly to pinch grip force capacities, peak pinch grip force used while handling an object is affected by the object's surface friction. Similarly to Kinoshita's findings, both generations were observed to be affected by friction (Kinoshita & Francis, 1996). During a grip, normal forces must be applied to create tangential forces equal or larger than gravitational forces to prevent slip and hold up a given object. Prior research suggested that pinch grip force was inversely scaled to friction (Cadoret & Smith, 1996; Cole & Johansson, 1993; Edin et al., 1992; Flanagan, J. Randall & Wing, Alan M, 1997; Gilles & Wing, 2003; Johansson, 1996; Johansson & Westling, 1984; Kinoshita & Francis, 1996; Westling & Johansson, 1984). Therefore grip force was expected to be larger in the low friction condition than in the high friction. However it was found that peak grip force in the low friction condition was always lower for both ages across all trials. It is believed that while on high friction objects people applied a tremendous amount of force to secure their grip, they had to apply a slightly lower force in low friction by fear of thrusting the apparatus out of their grasp with a too strong grip as they hit the limit. It is also supposed that similarly to the stationary pinch grips observed, people were also more cautious performing the task with slippery objects. These findings are corroborated by Engel et al. (Engel et al., 2010) who state that in low friction, grip application must be precise due to the cone of friction being narrower, therefore there are less muscle coordination patterns to successfully grasp the object resulting in lower grip force. They hypothesised that individuals are able to produce greater grip force on high friction objects. Moreover, in the literature cited low friction conditions were represented by smooth textures such as leather or smooth plastics, whereas in the present work petroleum jelly was creating an extremely low coefficient of friction. The grip was therefore extremely unstable and hazardous as the object could all too easily slip out of grip. It is therefore thought that people showed lower grip force in low friction due to the extremity of the situation, and felt they had to be precise and thus lowered the grip force they applied to avoid slippage. It is thus hypothesised that when exposed to extremely slippery objects and while performing rapid, brusque and hazardous handling movements people apply a lower force than they would in high friction conditions, because they feel the need to be more cautious and precise in order to be successful and not drop the object.

The Stationary Experiment exhibited the existence of a maximal grip force capacity plateau with object size over hand size. The Perturbation Experiment, by testing objects covering approximately this region, demonstrated that as long as the object to be pinched sits within this force plateau, then its size does not affect the force used to handle it. However once an object reaches people’s aperture limits, it suddenly becomes impossible to lift and handle such object. This situation changes drastically and was observed with the widest object that could not be lifted by many in the low friction condition. As the object gets too wide it becomes inconvenient for the user to pinch it; the grip force angles become too important. When both finger pads are parallel, and supposing the grip force is applied perpendicularly to both surfaces, the forces necessary to lift a given object will depend on its weight and its surface friction. In this situation, the higher the grip force the more secure the grasp. Therefore inability to lift the object results from the inability to apply sufficient grip forces. From the instant the finger pads are no longer parallel the cone of friction comes into play. It then dictates the stability of the grip, and increasing the grip force does not induce a more secure grasp, as it can result in the increase of a thrust force. The wider the angle between the two finger pads, the closer to the edges of the cone of friction the grip force gets, reducing ever more the muscle coordination patterns to successfully grasp the object. Past a certain width the finger pads are too far from the rounded ends apexes, and cannot apply a force within the cone of friction, the object thus slips out of grasp. People's struggle depends therefore on the object size and its surface coefficient of friction. The slip force depends on the mass of the object but also on the coefficient of friction of the contact area between skin and object's surface. Similarly to what had been expected slip force was found to be dependent of the coefficient of friction of the object's surface for the entire population.

In the continuity of this thesis main research's aim, a younger and older population were sampled to investigate the effects of ageing on grasp. Sampling distinct and diverse populations highlights their similarities and differences. Young and older people are different in a wide range of aspects. Opening one's hand tends to become more difficult with age. The physiognomy and abilities of a human being are two important factors when it comes to pinch grip force, and consequently handling. During the contact phase of a reach-to-grasp-and-lift movement the grip force reflects the entire grasp system. It results from the user's capacities, the friction between the skin and the object, the object's characteristics, such as its mass, size, affordances, balance, and from inertial forces due to progressive or sudden accelerations in the motion. Interestingly, in both experiments age was found to have no effect on people's grip force, whether it was their grip force capacities, or grip and slip forces used during lift. On the other hand, older adults were found to drop the objects more often, reflecting a higher struggle in performing the lifting tasks.

Despite that, Gilles and Cole (Cole et al., 1999; Gilles & Wing, 2003) observed higher grip force for older people. They say that in both stationary and perturbed conditions older people apply a higher grip force than their younger counterparts. They suggested that it is the loses of mechanoreceptors with age, and the deterioration of the skin that give older people a lower coefficient of skin friction. Kinoshita observed the same higher force with older people and agrees with them by suggesting that it is due to a decline in tactile mechanisms and a regression of CNS functions. However, this latter point is not unanimous, Gerhardt declared that changes in skin properties with age are in the form of a decrease in elasticity, and an increase in hydration but not in skin friction (Gerhardt et al., 2009). Hydration seems to be an important determining skin factor, because the dynamic of fingertip contact depends on skin hydration, and the safety margin used in precision grips increases with skin hydration (Andre et al., 2011). On the other hand, André stated that dry skin forces higher grip force. Furthermore, Gilles found that safety margins were consistent across ages, similarly to what has been observed in this chapter, while Cole observed older people's safety margins being twice as large as young ones.

However care must be taken because the older cohort was however mainly consisting of women. According to the results obtained in the Stationary Experiment, it can be speculated that women have lower grip force, but the difference is lessen with age, resulting in older women applying larger pinch grip forces than younger women. Therefore it is thought that the averaged grip force of the older cohort could have been even higher if more older male subjects had taken part in the experiments. Maybe older people's grip force would have been observed to be higher than the one of young people, similarly to Gilles and Cole's findings.

As explained in Chapter 2, Cambridge designed impairment gloves, referred to as Cambridge Impairment Simulator Gloves (CISG), which consist of plastic stripes wrapped along each digit reducing thus their dexterity and making fist formation more difficult. It has been demonstrated in Chapter 5 that these gloves force young adults to behave in similar ways to older people during their reach-to-grasp actions' pre-contact phase. While the gloves force a slower reach-to-grasp movement, they did not appear to have any effect on grip force. Against all predictions only slight and insignificant higher forces were observed with CISG, approximately 2 N. The author predicted that CISG, designed to significantly reduce people's hand dexterity, would prohibit people from applying the force they can reach with a free healthy hand. Yet since no significant differences were found in force capacities and force use between older and younger adults it is not too surprising that lower dexterity does not generate differences. The CISG are designed in such a way that the more people are closing their hand to form a fist the more difficult it gets due to the increasing resistance from CISG. It can therefore be hypothesised that CISG could have a significant effect on grip force for tiny objects requiring finger pinch grip apertures smaller than the ones investigated in this study. Also, as CISG is affecting the entire user's hand, the effect could be more significant on tasks based on multiple digits use.

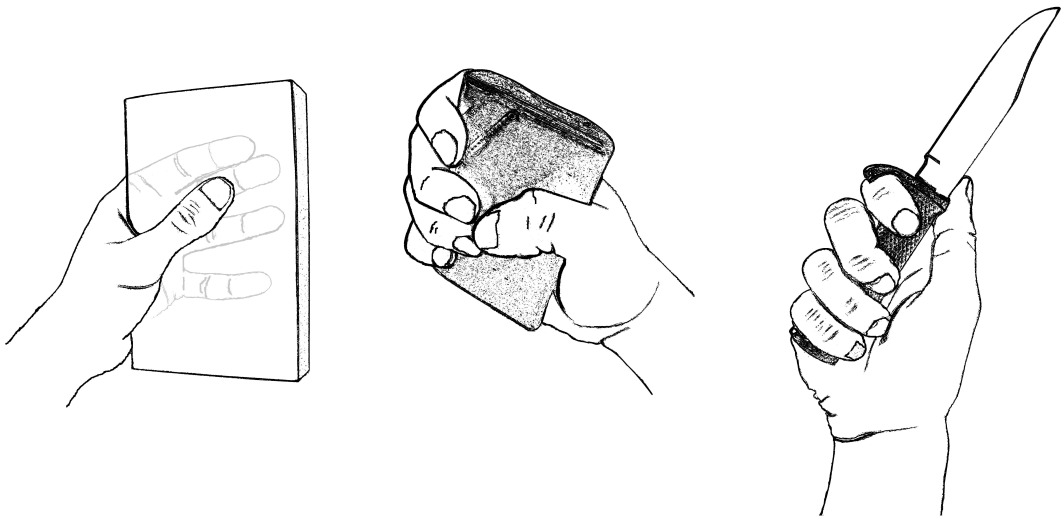
If the present work was to be tested further, and for instance tested on different objects, some guidance for equipment and protocol improvements in terms of precision and accuracy can be given. The apparatus could be improved by the addition of a location sensor (Westling & Johansson, 1984), which would give the course of the object during lift, and the precise instant the object is dropped. Moreover, replacing the Dytran dynamic force transducer by a static one would result in accurate measurements of grip force all along the duration of the trial, even as the object is slowly released to be dropped. This would thus make the Honeywell load cell obsolete, as well as the extruded cut designed for it to be slotted in the apparatus, both impairing one end of the stimuli, affecting tactile perception and the contact area. Better load readings could be then collected. The procedure could also be improved by reducing the speed at which participants had to release the apparatus, thus making sure to obtain a graded reduction of grip force for a smooth initiation of slip force. Plus, having them hold the apparatus stable in the air for longer would allow grip force to stabilise. The grip force would stabilise to the force people normally apply to hold such object, which could be compared with the peak and slip force. All these improvements would result in better slip force and grip force readings in diverse handling situations, from which more accurate safety margin could be deduced.

In summary, there is a region defined by the ratio between object and hand size where grip force capacities are at their maximum. It is the most convenient region for users to handle products and where most of the handheld tools fall in. When handling objects people use a grip force lower than what they can produce. Even if grip force has to be significantly raised to cope with a perturbation, they never squeeze an object as hard as they could just to handle it. No significant differences were observed in terms of force capacities and use between generations and dexterity conditions. Safety margins were obtained from the peak force applied to cope with a sudden and unpredictable stop and are therefore significantly larger than what can be read in existing literature. Consistency in handling was observed across all trials, because as long as the object size remains within a manageable size region (i.e., the plateau region) than object width does not affect pinch grip force. This analysis of the contact phase and evolution of grip forces during object handling completes the work done in the previous chapter and its study on the pre-contact phase of a reach-to-grasp-and-lift movement. The following chapter focuses on extending this work by investigating the reach-to-grasp-and-lift movement's pre-contact phase for a power grip on a common handheld tool used in real life. The purpose of such work is to apply the theoretical work studied so far to a product people can relate to.

Chapter 7

Power Grip Reach-to-Grasp in Older Adults

Handgrip is a primate's attribute, the order that we come from, because it can only be achieved thanks to opposable thumbs resulting in the great dexterity in our upper limbs. As Napier outlines (Napier, 1956), hand grip can be categorised into two distinct grasp techniques: pinch and power grip. From biology to robotics including ergonomic and engineering, many diverse research areas have looked into those two grasp techniques. Pinch grip is the act of squeezing an object between two digits, typically the thumb and index finger. The two fingertips tend to face one another to create two opposing forces clutching the object in a stable grasp. Research has focused primarily on the two-digit pinch grip, the reason being that while multi-digits grasps are inherently more stable, the index-thumb grip is the basis of any grasp technique and is more straightforward to study and represent mathematically. Nevertheless, a pinch grip as such is a very basic grip interaction, and humans will use more than two digits to handle an object in many situations as more digits allow more stability. A power grip permits more muscle coordination patterns, more force and more stability. Simply adding a third finger to the grip increases the number of degrees of freedom, possible directional forces, and multiplies grasp stability states to be processed by the CNS (Flanagan et al., 1999). Consequently a power grip where up to five digits, 14 phalanges and one entire hand palm interact with an object is significantly more sophisticated. In a power grip the object is placed against the palm of the hand and the fingers enclose it by adopting its shape (Figure 7.1). If the object is large enough the thumb is facing the other four fingers on the opposite side of the object, clamping it as a result. Power grip is preferred to pinch grip when stability, and force are required over precision and subtlety. The contact phase of a power grip is significantly different from a pinch grip due to the skin-product contact area and the forces involved. The hand can adopt a multitude of shapes; grasp stability depends on many variable factors such as every phalangeal joint's range of motion, diverse skin area sensitivity, tendon tensions, and a wide range of force distribution achievable. Therefore to study the contact phase of a power grip sophisticated apparatus are required, which would require development beyond the scope of what is possible in this thesis, given the other work undertaken. However, considering the approach for a power grip as a combination of a hand motion towards the object and a grip aperture creation, it can then be analysed in the same way as a pinch grip approach phase, considered in Chapter 5 as a combination of a hand motion towards the object and a grip aperture creation.



(a) **(b)** **(c)**

Figure 7.1 Depending on the object affordance, in a power grasp the hand is adopting different shape to grasp it, whether it is (a) a book, (b) a mobile phone, or (c) a knife.

This chapter uses the same paradigm applied in Chapter 5 to study the pinch grip reach-to-grasp actions, and see whether the same changes in targeting and collision avoidance are evident when using a power grip. The study of people's behaviour in the pre-contact phase of a reach-to-pinch-grip motion is the first step toward understanding user product interaction, but remains extremely theoretical. Humans rarely rely solely on a two-digit pinch grip when handling objects, and in a kitchen environment power grasp is the interaction technique used to handle many utensils. So to better understand how product properties influence human behaviour, and therefore be able to improve products design to facilitate older people's life with more adapted tools (more specifically kitchen tools), handgrip data has to be extended to a more general user-product interaction. This implies testing power grips, and observing people reaching for familiar objects. To draw the laboratory testing closer to real life handling situations, this chapter presents a study where subjects were asked to reach-to-grasp-and-lift a kitchen pan. Chapter 5's study was therefore adapted to a more realistic kitchen based situation, a situation that participants could relate to.

The study displayed here observes people's behaviour as they reach to grasp a pan by dissecting their movement into different metrics. The interest of this chapter is to see how these kinematic values, such as hand speed and finger aperture, are affected by the pan's handle characteristics and location. This study is also an adaptation of the study of Chapter 5, where all the tests were done on pinch grip actions. The protocol used and metrics measured in both studies were identical. This was possible because the reach-to-grasp for pinch and power grips both involve the same stages: a hand acceleration and deceleration, and a finger grip aperture formation, and closing. Similarly to Chapter 5, the effects of object width, surface friction, and location were analysed with two distinct age groups emphasising the possible effects of age on a reach-to-grasp actions for power grip on a familiar item.

7.1 Methods

7.1.1 Participants

The present study is an adaptation of the study presented in Chapter 5. The same protocol and equipment were used to observe the kinematics of a reach-to-grasp-and-lift motion when reaching for a real life product: a pan. Twelve paid young participants (age mean 27.3 years, age range 22 – 40 years; six females; 12 reported right hand preference), and twelve paid older participants (age mean 72.92 years, age range 63 – 85 years; 10 females; 11 reported right hand preference) were recruited. All participants had normal or corrected-to-normal vision and no history of neurological deficit. Maximum pinch grip aperture was measured for each participant (mean 15.04 cm, range 12.5 – 17.5 cm for the younger group; mean 14.25 cm, range 12.0 – 16.0 cm for the older group). All participants provided informed consent prior to inclusion in the study, and received £5.00 for taking part in the study. They were randomly selected from a list of contacts, and recruited by email or phone. They were completely naïve with regard to the present study's purpose. The study was approved by a University Ethics Committee.

7.1.2 Procedure

Participants were asked to reach, grasp, and lift wok pans by their handles. The handles, always oriented towards subjects, were 10 cm long nylon cylinders specially manufactured for this study. The cylinders were fixed to the woks in place of their original handles. The handles' axis of revolution was at an approximate 15° angle from the tabletop. Participants were to grasp the cylinders along their lengths with their whole hand; producing then a power grasp around the handle of the wok. Handles differed in diameter (or width); they were representing a narrow, medium and wide stimulus, respectively with diameters of 30, 60, and 90 mm; the narrow, medium and wide stimulus 'widths' respectively (Figure 7.2). For each of the three stimulus widths, there were two different finishes applied to the grasp surface such that two distinct coefficients of friction would be generated. The high coefficient of friction resulted from the material characteristics of the as machined stimulus. The low friction condition was achieved through the application of petroleum jelly (Vaseline®, Unilever) with a soft-bristled brush to the grasp surface of the stimulus between trials of this condition (application was repeated on alternate trials).

Participants stood in front of a normal height table. To ensure a consistent starting position the participants pointed down their index finger on a raised origin marker positioned 5 cm from the front edge of the study table prior to the start of each trial. The pans were placed so that the point on the handle at which participants were expected to grasp it was at a 10, 30, or 50 cm distance beyond the origin point in line with the sagittal plane of the participant. Participants were instructed to reach and grasp the object with their dominant hand as quickly and as accurately as possible with their palm placed on top of the handle (Figure 7.2). In the same motion they then had to lift the pan from the table and hold it in a static raised position until told to lower the object back onto the table and return to the start position in preparation for the next trial.

(a) **(b)** **(c)**

Figure 7.2 Three power grip conditions (a) narrow (30 mm), (b) medium (60 mm), and (c) wide (90 mm) once the handle is grasped from the top.

The stimuli conditions were presented in a randomised order. Trials were grouped by the surface's coefficient of friction, randomly presented from one participant to the next. High friction and low friction trials could not be randomly alternated because jelly traces on fingers could have altered the as machined stimuli's coefficient of friction. The young cohort tested 18 conditions (i.e., three object distances, two coefficients of friction, and three object widths) while the older tested 12 (i.e., three object distances, two coefficients of friction, and two object widths). The younger cohort was recruited first, and because only two participants managed to lift the widest handle it was then decided to withdraw it from the tests presented to the older cohort. Ten successive reach-to-grasp-and-lift movements were repeated for each stimulus combination, varying in handle width, handle surface coefficient of friction, and pan distance from table edge resulting in a total of 180 trials for the young adults and 120 for the older adults. The kinematic data was recorded through the use of NDI Optotrak motion capture system, and infrared markers. Infra Red Emitting Diodes (IREDs) were placed on the index' proximal interphalangeal joint, on the thumb's distal phalange, on the styloid process of the wrist and on the stimulus where the handle was screwed to the pan bowl.

On the oral signal "Go" from the researcher, participants had to reach the object, power grip its handle and lift it. The participants were asked to grasp the pan handle from on top because otherwise the markers on the fingers would have been obscured from the cameras by the pan. The researcher appreciates that it might have made the task more difficult, as it might not have been the way they would normally grasp a pan, and that this technique limited the amount of grip force they could apply directly in opposition to gravitational forces under the handle. However this constraint ensured consistency, plus as observed in the study of Chapter 4 it was the most frequently used grasp technique. Consistency in wrist orientation was taken seriously since it has a great influence on users' grip force for both pinching and power gripping (Bensmail et al., 2009; Hallbeck, 1994; Imrhan, 1991; Li, 2002). Data acquisition started prior to any movement of the hand, and lasted five seconds resulting in participants having to hold the object in the air for approximately 0.5 to 1.5 second. A trial was considered failed when participants could not lift the pan up within the given time, or the pan was dropped before the end of the allocated time. After three failed trials the condition was skipped. Unlike Chapter 5 where the objects could easily be knocked over, or slip out of grasp for careless and inaccurate reach-to-grasp actions, a failed trial resulted here from the inability to lift the pan. Therefore if subjects could not lift the pan or hold it after three attempts they could never have performed ten successful trials. The test sessions typically lasted 50 minutes.

7.1.3 Measures

By reading the location of the IREDs, the Optotrak tracking system provided the kinematic data of the hand and pan movements. The measure of the distance between the two finger makers indicated the subject's grip aperture. The wrist marker provided an independent measure of hand speed, and movement duration. The last marker, placed on the pan, indicated the moment when the pan was lifted off the tabletop. The instant at which the IREDs' velocity exceeded 50 mm/s defined the onset time. The offset time was determined by the moment at which the velocity dropped below the threshold velocity of 50 mm/s. The duration of movement was calculated from the time at which the maker was in motion (i.e., onset time) to the time it stopped (i.e., offset time). Between the onset and offset times the maker was considered in motion, whether it referred to the hand or pan. Similarly to Chapter 5, a lift was considered as a 'fly-through' if the wrist's velocity never dropped below the threshold velocity before the pan was in motion, otherwise the movement was considered as a 'stop-and-go'.

The velocity of the markers allowed the determination of the hand movement time defined as the difference between the onset time of the pan and the onset time of the wrist. The time to peak speed referred to the time taken by the hand to go from the threshold velocity to its maximal velocity. The second time metric was the elapsed time from the moment the wrist was in motion until the moment the thumb and index finger reached their maximal aperture. The maximum grip aperture is the widest distance between the thumb and index reached during the movement, in other words when the hand is open at its widest over its reaching course toward the pan. Additionally, the time people spent adjusting their grip around the handle before lifting it in a 'stop-and-go' movement was calculated. This dwell time was defined as the difference between the onset time of the pan (IRED 4 exceeding threshold velocity) and the offset time of the wrist (IRED 3 dropping below the threshold velocity). Comparably to Chapter 5, the times to reach peak speed and maximal grip aperture were also normalised over the overall hand movement for better movement phase's comparison between age groups.

The kinematic measures, identical to the ones measured in Chapter 5, analysed and compared in this study were therefore: peak speed (PS); time to peak speed (tPS); maximum grip aperture (MGA); time to maximum grip aperture (tMGA); normalised time to peak speed (ntPS); normalised time to maximum grip aperture (ntMGA); dwell time (dwell); and movement time (MT). The wrist IRED was placed at the identical location as it was during the pinch grip experiment. The object IRED was located on the object like in the pinch grip experiment, and thus reflected the same information on the movement of the object. Caution must be taken for the MGA values, because the digits markers were not placed at the exact same location as in the pinch grip experiment, otherwise the pan would have obscured them from the cameras during grasp.

Taking the medium size (60 mm diameter) pan in the high friction condition placed at 30 cm from the starting point as an example of a specific set of experimental conditions. Participants will start displacing their hand towards the object, starting from a null grip aperture and a null hand speed, they will accelerate the motion of their hand to reach a peak speed of about 717 mm/s for older adults, and 764 mm/s for young adults. Their PS is reached approximately 411 ms after movement initiation for older, and 367 ms for young. At the same time, people are progressively widening their grip aperture to reach an MGA (maximal distance between index and thumb) of 79.4 mm for older, and 85.9 mm for young. This MGA is reached 397 ms after movement initiation for older, and 421 ms for young. In these conditions, the acceleration and opening phases represent respectively 14% and 29% of the overall movement time for older adults, and 21% and 30% for young adults. In a following phase, people then decelerate and reduce their grip aperture until they arrive on the pan handle; it must be noted that the deceleration and closing phase do not necessarily match. The entire approach phase lasts approximately 1617 ms for older, and 1287 ms for young. In the case where hand speed drops below 50 mm/s and a 'stop-and-go' movement occurs, then a dwell time is observed to last 452 ms for older, and 256 ms for young. Too few 'stop-and-go' motions were observed for older adults for this average value to be accurately representative and tenable. A summary of all the movement data and measured time and distances is given in Table 7.1.

Table 7.1 Average movement data of all the kinematic values examined in all the conditions for the older and young adults in both friction conditions during power grasp reach-to-grasp.

Friction	Group	Distance	Width	MT (ms)	MGA (mm)	tMGA (ms)	ntMGA	PS (mm/s)	tPS (ms)	ntPS	Dwell (ms)
High Friction	Older adults	Close	Narrow	1404	72.0	243	20%	469	409	16%	305
			Medium	1457	80.0	355	28%	460	393	17%	548
		Middle	Narrow	1546	66.5	251	21%	686	391	14%	682
			Medium	1617	79.4	397	29%	717	411	14%	452
		Distant	Narrow	1663	62.6	230	18%	850	452	16%	330
			Medium	1788	72.5	313	22%	826	468	15%	364
	Young adults	Close	Narrow	1200	72.5	280	23%	477	365	22%	312
			Medium	1214	86.2	392	31%	514	357	21%	323
		Middle	Narrow	1254	73.5	214	17%	734	374	20%	231
			Medium	1287	85.9	421	30%	764	367	21%	256
		Distant	Narrow	1438	69.3	206	15%	927	444	21%	195
			Medium	1429	80.5	446	31%	951	436	21%	215
Low Friction	Older adults	Close	Narrow	1393	70.4	321	24%	526	394	15%	410
			Medium	1469	83.5	390	31%	435	402	15%	502
		Middle	Narrow	1549	67.8	273	22%	707	409	14%	475
			Medium	1792	80.4	394	30%	710	424	14%	545
		Distant	Narrow	1678	66.1	279	20%	858	464	15%	773
			Medium	1791	80.6	342	27%	882	458	14%	506
	Young adults	Close	Narrow	1195	73.2	245	21%	440	373	21%	322
			Medium	1257	86.8	489	35%	503	377	22%	366
		Middle	Narrow	1298	69.0	326	25%	726	369	19%	173
			Medium	1365	85.5	497	34%	696	368	20%	305
		Distant	Narrow	1509	69.5	308	22%	899	483	23%	211
			Medium	1510	78.2	485	32%	896	451	22%	278

7.2 Analysis

The two population cohorts investigated in this research matched the age groups of Chapter 5. For statistical purposes participants had to record ten successful lifts in every condition. Once these ten successful lifts were recorded the participants moved on to the next condition, unless they accumulated three unsuccessful lifts before securing the ten required lifts. Unlike the object tested in Chapter 5, one failed attempt often presaged three failed, and thus a failed condition. As explained in Section 7.1, an attempt was considered as unsuccessful (i.e., a 'fail') when people could not secure the object in the time allocated, or when the object slipped out of their grasp unintentionally whether they had managed to lift it or not. Even if the older people exhibited more struggle these evaluation conditions were kept identical for every participant. The object had to be kept stable in the air until the recording was over. In the case where three unsuccessful attempts where observed before ten successful ones were recorded then the test was abandoned and skipped, no data was then kept for that particular participant for that precise condition.

For each cohort a repeated measures ANOVA (surface friction (2) x distance (3) x object width (2)) was carried out on each kinematic measure averaged across the ten trials recorded per condition for each participant. In order to identify the significance of the possible effects of age, a repeated measures ANOVA paired by cohorts was also run (a separate ANOVA for each dependent variable of interest). Partial eta squared (η^2) values are reported for statistically significant findings. The data were tested for violations of sphericity, and where assumption of sphericity was not met, Greenhouse-Geisser corrections of epsilon (ε) were applied to the degrees of freedom. The variability of the reported measurements is graphically represented as error bars in this chapter. They are a representation of the standard error of the mean (SEM), which is calculated with the sample standard deviation divided by the square root of the sample size.

7.3 Results

Proportion of Failed Tests in the Young Cohort

In the high friction condition, up to three subjects of the young cohort could not lift the widest handle, and up to ten could not do it in the low friction condition (more than 50% of the wide handle trials were skipped across all conditions for the young cohort). No statistical analysis could be done on the data of the widest handle for the young cohort due to this extremely high failure rate (80% of the participants could not lift it in the low friction condition). Therefore the wide handle was not presented to older people in either condition. Nonetheless, the middle width handle remained too tedious to lift for up to three older subjects in the low friction condition (Figure 7.3).

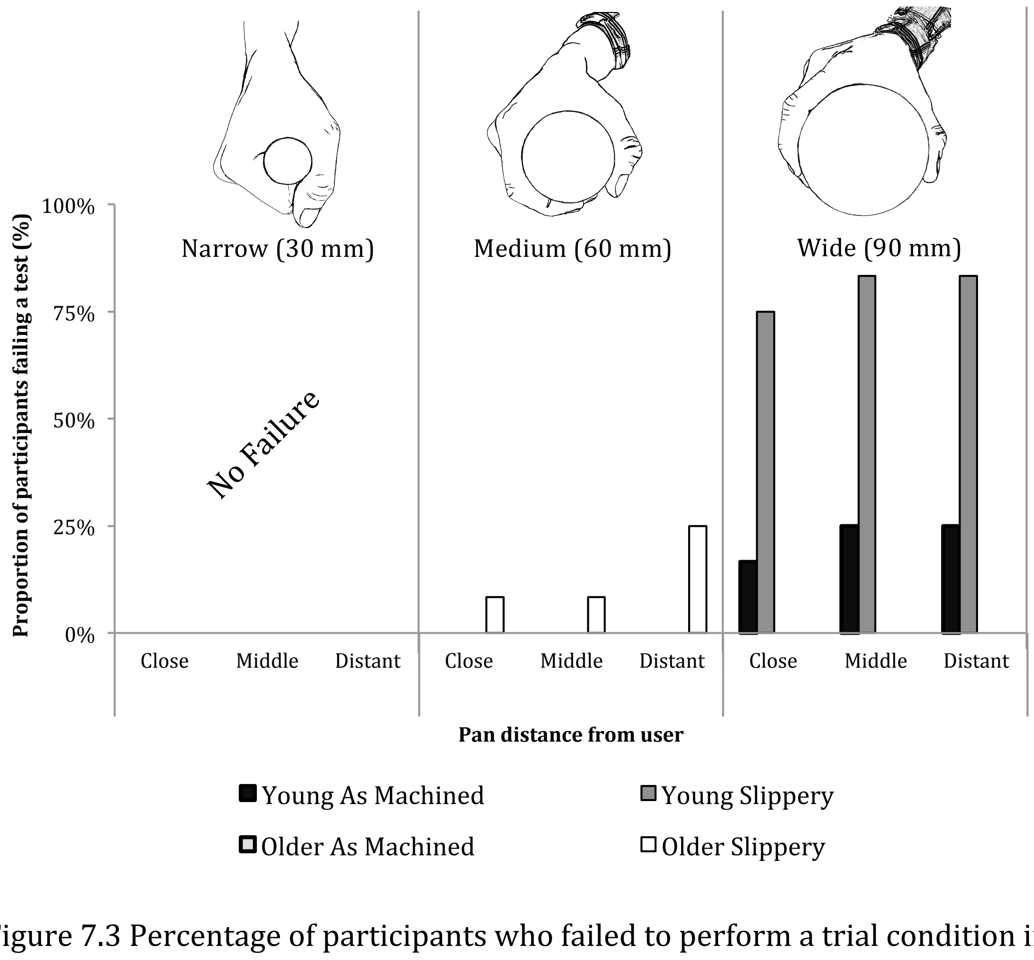


Figure 7.3 Percentage of participants who failed to perform a trial condition in both friction conditions. The wide condition was not presented to the older group.

A repeated measures analysis was run on the number of failed trials for the young cohort data since they tried all the combinations and failed a considerable proportion of those. It was found that the surface's coefficient of friction had a significant effect on the proportion of failure ($F(1,11) = 18.169$, $p < 0.01$, $\eta^2 = 0.623$). The more slippery the object, the less likely people were to be able to lift it. The wide handle was significantly harder to pick up ($F(2,22) = 30.670$, $p < 0.01$, $\eta^2 = 0.736$). There was a significant interaction between object width and friction ($F(2,22) = 18.169$, $p < 0.01$, $\eta^2 = 0.623$). Failures only occurred with the widest handle for young adults and significantly increased with lower surface friction.

Movement Time (MT)

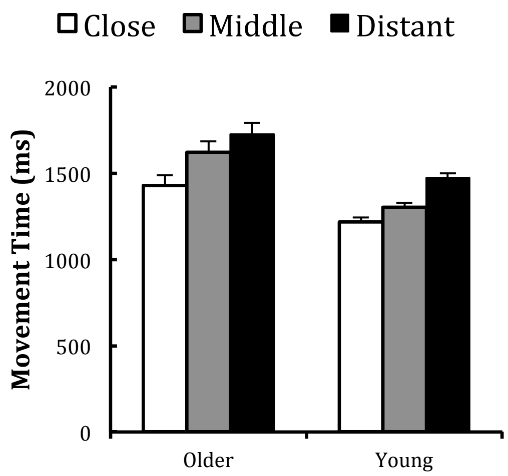


Figure 7.4 Aggregated Movement time values for all subjects across both friction conditions grouped by object distance from user.

There was a significant effect of distance ($F(2,22) = 35.056$, $p < 0.01$, $\eta^2 = 0.761$), but no significant effect of object width ($F(1,11) = 1.315$, $p = 0.276$) or friction ($F(1,11) = 1.898$, $p = 0.196$) on the overall movement time of young adults. Further objects forced young people in having a longer MT.

There was no effect of friction ($F(1,8) = 0.086$, $p = 0.777$), but there was a significant effect of distance ($F(2,16) = 16.860$, $p < 0.01$, $\varepsilon = 0.578$, $\eta^2 = 0.678$) and object width ($F(1,8) = 13.164$, $p < 0.01$, $\eta^2 = 0.622$) on the overall movement time of older adults. Further and wider objects forced older people in having a longer MT.

A paired repeated measures analysis (i.e., young vs. older) was run to determine the importance of the effects of age. It revealed that older participants had MT longer than young participants ($F(1,19) = 5.151$, $p = 0.035$).

As predicted, as the object was placed further from the user the movement time (i.e., time to reach the object) was longer for all people (Figure 7.4). However it is interesting to notice that with wider objects, forcing a larger grip aperture, the movement time was also longer for older people. Additionally MT increased across trials with age, reflecting that older people took more time to reach-to-grasp a pan than younger adults.

Proportion of 'Stop-and-Go' Movements and Dwell Time

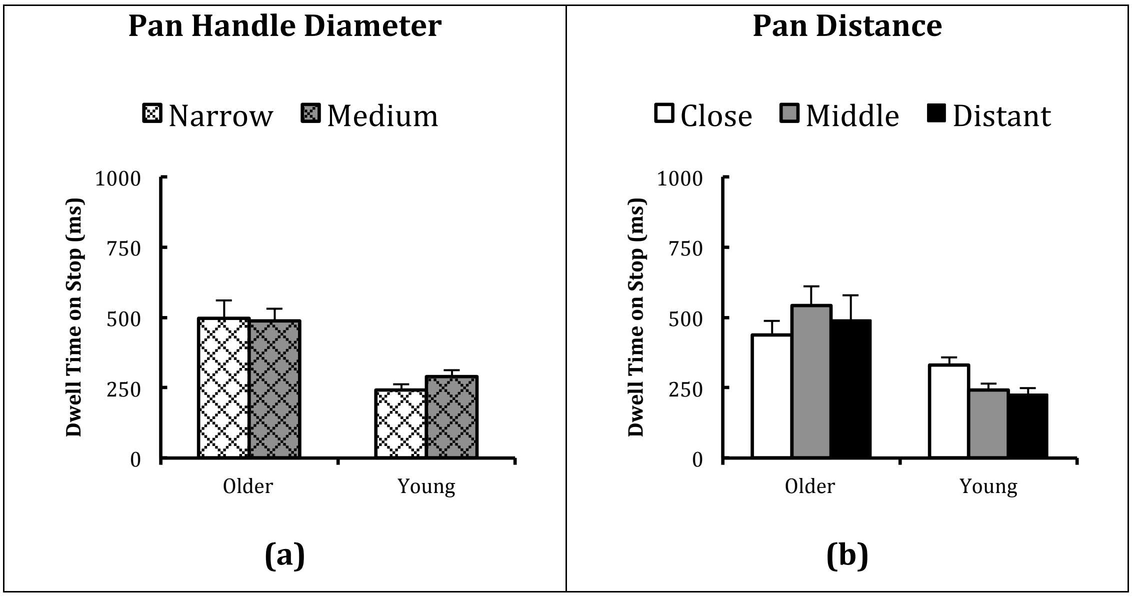


Figure 7.5 Aggregated Dwell Time values for all subjects across both friction conditions grouped by object width and object distance from user.

There was no significant effect of friction ($F(1,11) = 1.863$, $p = 0.200$), distance ($F(2,22) = 2.951$, $p = 0.073$), or object width ($F(1,11) = 0.328$, $p = 0.578$) on the proportion of 'fly-through' movements for young adults. Young adults were constant in their reach-to-grasp action's structure, because they approximately stopped to secure their grip on every attempt across all trial conditions. On those stopped attempts, distance ($F(2,22) = 10.798$, $p < 0.01$, $\eta^2 =$

0.495), and width ($F(1,11) = 5.465$, $p < 0.05$, $\eta^2 = 332$) had a significant effect on their dwell time (i.e., time spent adjusting grip around object before lifting it), but not friction ($F(1,11) = 1.129$, $\varepsilon = 0.514$, $p = 0.726$). Young adults increased their dwell time with object width and decreased it with distance.

There was no significant effect of friction ($F(1,8) = 2.180$, $p = 0.178$), distance ($F(2,16) = 0.693$, $p = 0.515$), or object width ($F(1,8) = 1.487$, $p = 0.257$) on the proportion of 'fly-through' movements for older adults. Older people were constant in their reach-to-grasp action's structure, because they approximately stopped to secure their grip on one fourth of their attempts across all trial conditions. The quantity of 'dwell time on stop' data obtained for the older population was therefore significantly smaller than for the young one. Older people rarely sequenced their reach-to-grasp actions, leading to a small amount of dwell time readings, prohibiting tenable statistical analysis on older people's dwell time and on comparison between age groups.

Object friction, distance, and width had no significant effect on the structure of reach-to-grasp action in terms of 'fly-through' and 'stop-and-go' motions for people of all ages. Nevertheless, younger people did need more time to secure their grip around wider objects (Figure 7.5(a)), but less time with further objects (Figure 7.5(b)). Interestingly, friction had no significant effect on their dwell time. Ignoring the widest handle, young subjects paused their movement as they reached the pan before lifting it up almost on every trial (94.32%), while older people's 'stop-and-go' motions represented only a quarter of all their trials (26.81%).

Maximum Grip Aperture (MGA) and Time to Maximum Grip Aperture (tMGA)

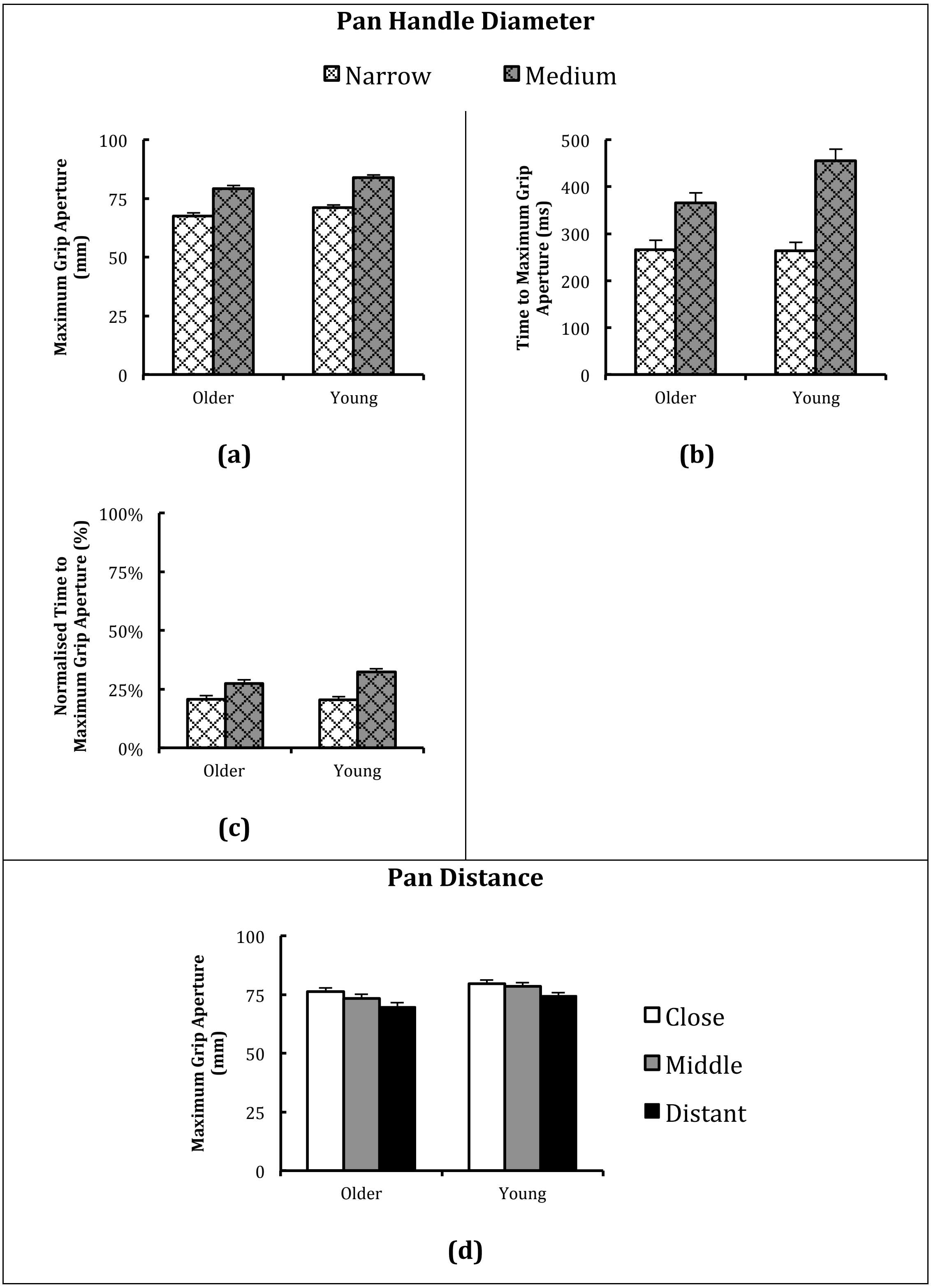


Figure 7.6 Aggregated kinematic values for all subjects across both friction conditions grouped by (a) object width and (d) distance from user for MGA, and by object width for (b) tMGA and (c) ntMGA.

On the maximal grip aperture of young adults, friction had no significant effect ($F(1,11) = 0.618$, $p = 0.449$), while distance ($F(2,22) = 18.811$, $p < 0.01$, $\eta^2 = 0.631$), and width ($F(1,11) = 48.432$, $p < 0.01$, $\eta^2 = 0.815$) caused significant differences. There was a significant interaction between distance and width ($F(2,22) = 4.873$, $p < 0.05$, $\eta^2 = 0.307$). However friction ($F(1,11) = 5.291$, $p < 0.05$, $\eta^2 = 0.325$) and width ($F(1,11) = 13.517$, $p < 0.01$, $\eta^2 = 0.551$) had a significant effect on young adults' tMGA, but not distance ($F(2,22) = 0.097$, $p = 908$). The normalised time to Maximum Grip Aperture, or tMGA over the duration of the hand movement, was also affected by width ($F(1,11) = 12.892$, $p < 0.01$, $\eta^2 = 0.534$), but not by distance ($F(2,22) = 0.659$, $p = 0.527$) or friction ($F(1,11) = 4.543$, $p = 0.056$). As the object got wider, young people increased their MGA, tMGA, and ntMGA. Young people took more time to reach MGA when reaching for low friction objects, and used smaller MGA with more distant objects.

Similarly to young adults, there was a significant effect of distance ($F(2,16) = 4.869$, $p < 0.05$, $\eta^2 = 0.378$), and width ($F(1,8) = 49.230$, $p < 0.01$, $\eta^2 = 0.860$) on the MGA of older adults, but not of friction ($F(1,8) = 3.785$, $p = 0.088$). Friction ($F(1,8) = 2.209$, $p = 0.176$), and distance ($F(2,16) = 17.673$, $p = 0.219$) had no significant effect on older adults' tMGA, unlike width ($F(1,8) = 27.801$, $p < 0.01$, $\eta^2 = 0.777$). Similarly, the ntMGA was also affected by width ($F(1,8) = 15.752$, $p < 0.05$, $\eta^2 = 0.664$), but not by friction ($F(1,8) = 1.859$, $p = 0.210$) or distance ($F(2,16) = 3.506$, $p = 0.055$). Similarly to young adults, as the object got wider older people increased their MGA, tMGA, and ntMGA, and used smaller MGA with more distant objects. However unlike their younger counterparts they did not scale their tMGA with object surface friction.

Age had no significant effect on MGA ($F(1,19) = 0.594$, $p = 0.450$), tMGA ($F(1,19) = 1.113$, $p = 0.305$), or ntMGA ($F(1,19) = 0.545$, $p = 0.470$). There were no other interactions.

Similarly to pinch grip people of all ages positively scaled their power grip MGA to object width (Figure 7.6(a)). However, where in pinch grip actions people scaled their MGA in different ways to distance, for power grasps both age groups scaled it negatively to distance (Figure 7.6(d)). Increasing the distance increased the overall movement time, however it did not influence the time to reach MGA for anyone, unlike what was found for pinch grip, where tMGA was positively scaled to distance. Because increasing the width of the object forces an increase in MGA, it is not surprising that it also increases the time necessary to reach MGA (Figure 7.6(b)). On top of that, everyone increased their aperture opening phase with increasing object width (Figure 7.6(c)). When reaching to pinch grip young adults also scaled their ntMGA to distance, while no one did for power grasps. In general people took more time to reach their MGA when approaching low friction handles, but the differences in time between the two friction conditions were only significant for young people.

Peak Speed (PS) and Time to Peak Speed (tPS)

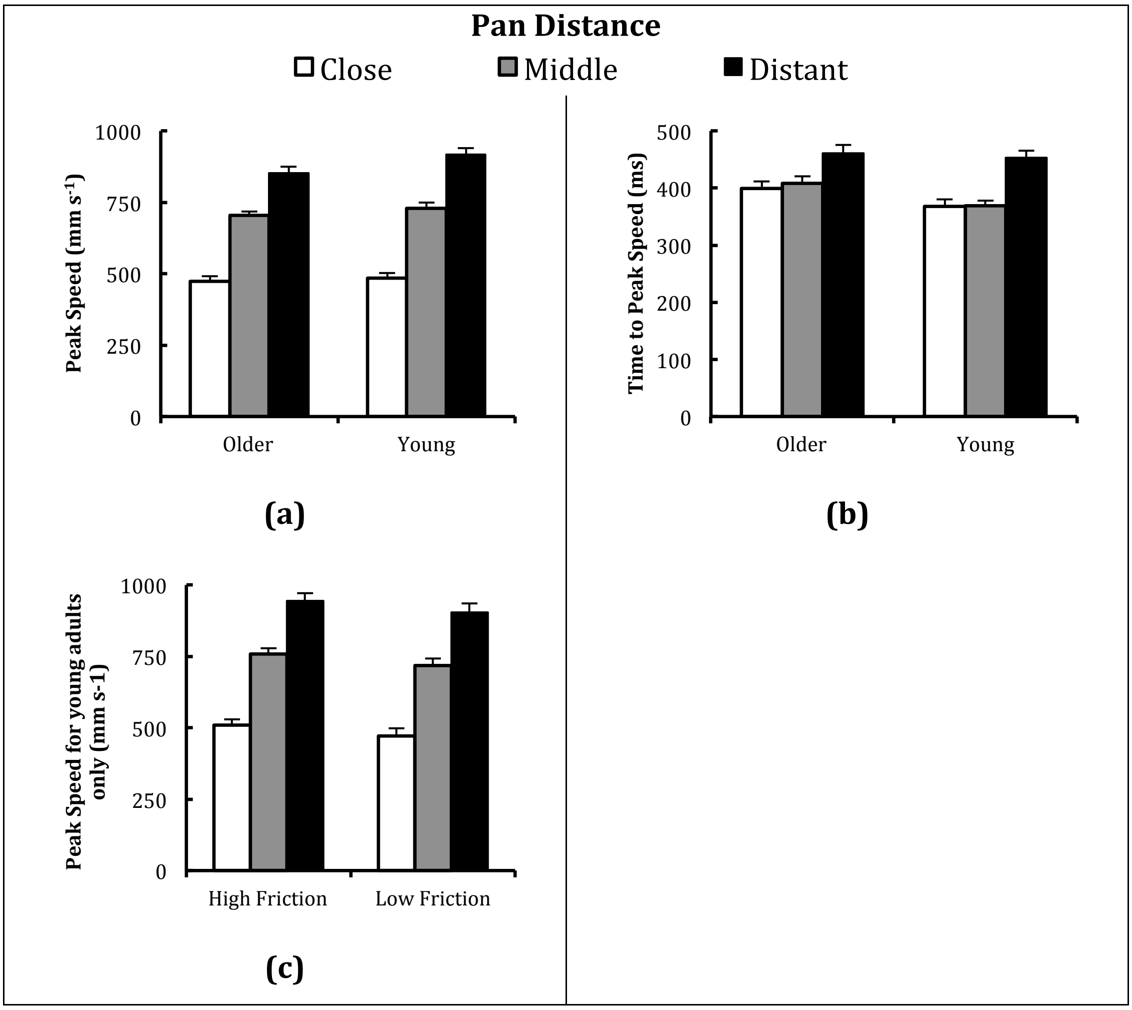


Figure 7.7 Aggregated PS and tPS values grouped by distance for all subjects across both friction conditions and for young in both friction conditions.

There was a significant effect of friction ($F(1,11) = 9.250$, $p < 0.05$, $\eta^2 = 0.457$) and distance ($F(2,22) = 249.709$, $p < 0.01$, $\eta^2 = 0.958$), but not of width ($F(1,11) = 3.064$, $p = 0.108$) on the peak speed of young adults. Distance had a significant effect on their tPS ($F(2,22) = 19.211$, $p < 0.01$, $\eta^2 = 0.636$), but not object friction ($F(1,11) = 0.599$, $p = 0.455$), or width ($F(1,11) = 1.976$, $p = 0.187$). The normalised time to Peak Speed, or tPS over the duration of the hand movement, was affected by neither friction ($F(1,11) = 0.024$, $p = 0.879$), nor distance ($F(2,22) = 2.304$, $p = 0.123$), nor width ($F(1,11) = 0.333$, $p = 0.576$). As the object was placed further away from them, young adults raised their PS and took more time to reach it. However, the ratio of their acceleration and deceleration phases did not suffer significant changes across trials. The object width had absolutely no effect on any of the young adults' peak speed metrics, and thus they did not suffer any significant change across width trials. Friction on the other hand affected young adults' PS; lower pan surface friction induced lower PS.

There was a significant effect of distance ($F(2,16) = 70.557$, $p < 0.01$, $\eta^2 = 0.898$), but not of friction $F(1,8) = 0.627$, $p = 0.451$) or width ($F(1,8) = 0.599$, $p = 0.461$) on the peak speed of older adults. Similarly, distance had a significant effect on their tPS ($F(2,16) = 7,743$, $p < 0.01$, $\eta^2 = 0.492$), but not surface friction ($F(1,8) = 0.010$, $p = 0.922$) or object width ($F(1,8) = 3.443$, $p = 0.101$). The ntPS was also affected by distance ($F(2,16) = 8.627$, $p < 0.01$, $\eta^2 = 0.545$), but not by friction ($F(1,8) = 5.299$, $p = 0.05$) or width ($F(1,8) = 0.121$, $p = 0.736$). As the object was placed further away from them, older adults raised their PS and took more time to reach it. In addition, the proportion of their acceleration phase over their reach-to-grasp action increased with object distance. The object width and surface friction had absolutely no effect on any of the older adults' peak speed metrics, and thus they did not suffer any significant change across width and friction trials.

There were no significant differences in PS ($F(1,19) = 0.205$, $p = 656$) and tPS ($F(1,19) = 0.470$, $p = 501$) with age. However, there was an interaction between friction and age for PS ($F(1,19) = 5.229$, $p < 0.05$, $\eta^2 =0.218$; Figure 7.8), and one between width and age for tPS ($F(1,19) = 4.866$, $p < 0.05$, $\eta^2 =0.204$).

Older people had a significantly smaller acceleration phase in relation to their deceleration phase compared with younger adults ($F(1,19) = 24.840$, $p < 0.01$, $\eta^2 = 0.567$).

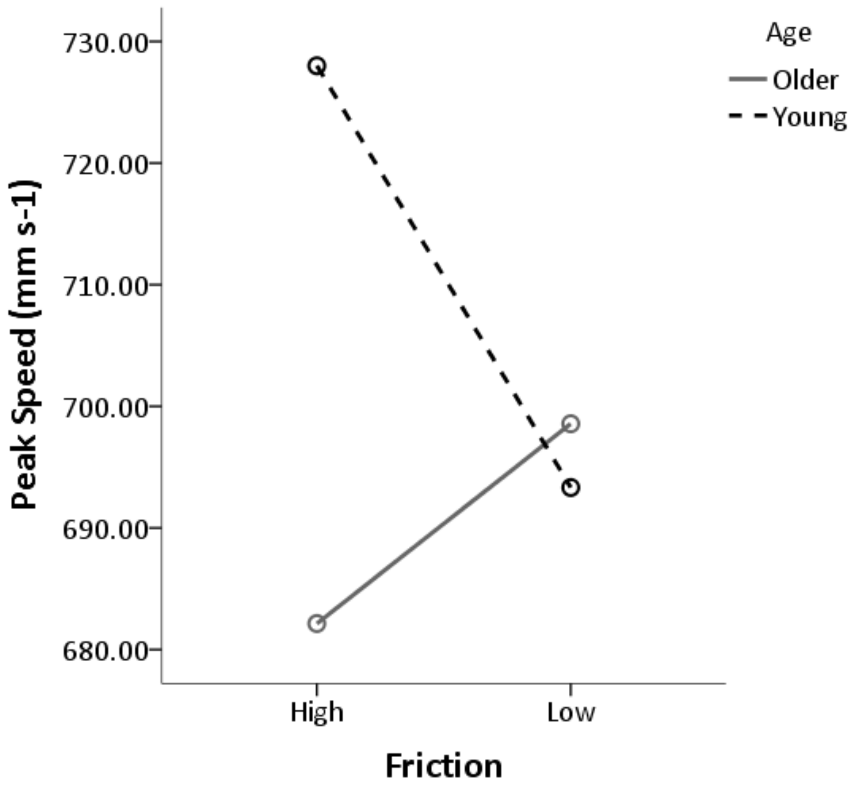


Figure 7.8 Interaction between friction and age for Peak Speed in power grip reach-to-grasp.

As it was suspected, the more distant the object was the more time it took people to reach it, and consequently the more time it took them to reach PS (Figure 7.7(b)). Additionally, with further object, people of all ages reached higher peak speed (Figure 7.7(a)). Young adults reached higher hand speed than older adults in a reach-to-grasp pinch grip actions, but not in power grasp actions. While young adults reached significantly higher PS in the high friction condition, older adults' PS did not appear to change with friction. Yet, the acceleration and deceleration phases of older people changed with object distance, while it did not seem to be the case with younger people. In relation to the duration of their hand movement younger adults reached peak speed later than older adults. Their pre-contact movement had therefore a longer acceleration phase and shorter deceleration phase.

7.4 Discussion

7.4.1 Power Grip Reach-to-Grasp Structure

In a power grasp there are more than two contact points, and thus force can be applied through every single one of them, whether it is a distal or proximal phalange of any digit or even the palm. Nevertheless, understanding reach-to-grasp-and-lift for power grips must not be disregarded due to its complexity. As a matter of fact it is an important and frequently used grasp technique.

The present study's goal was to investigate how age affected the transport stage of the reach-to-grasp movement when performed for a power grip, and how this compared with the changes identified in Chapter 5 where this was performed with a pinch grip.

In Chapter 5, it was observed that for pinch grip a low friction surface forces young adults to almost always sequence ('stop-and-go') their pinch grip reach-to-grasp, just like older adults who do it regardless of the object surface friction. For power grasp reach-to-grasp, friction was not found to have a significant effect on people's proportion of 'fly-through' actions regardless of their age. Oppositely to Chapter 5's results, young adults here predominantly stopped their reach-to-grasp to secure their grip before lifting the pan up, while older adults rarely stopped. Trial conditions (i.e., width, distance, friction) did not have any effect on either group's movement structure. Older people only stopped their reach-to-grasp on one fourth of their attempts, the proportion and distribution was such that no prediction can be made on whether a specific condition would result in a 'fly-through' motion for them. The fact that the pan could not be knocked over and that a power grip relies a lot less on friction than a pinch grip give sense to the absence of friction influence on people's reach-to-grasp. However, as older people are generally considered as frailer they were expected, regardless of the grasp technique, to always stop their motion more frequently than younger adults. By not being the case for power grasp, it is therefore hypothesised that if young people felt the need to secure their grip significantly more often than older people did is because they were not as familiar with the task as older adults were. It can therefore be hypothesised that older adults performed more 'fly-through' reach-to-grasp movements, because they felt at ease and confident in what was asked of them.

This experience that older people have gained with time, and that young students lack is thought to be an important factor affecting all the results. It is however in the proportion of 'stop-and-go' motion that it seem to appear most clearly. Regardless of the domain of expertise, with increasing practice and experience people's actions become smoother, less cognitively demanding, and less mistakes occur (Ericsson, 2006). It is thought that older people exhibited smoother movements because of their supposed greater experience.

The widest handle proved to be too difficult to lift specially in low friction conditions; leading to its removal for older people tests. Wider handles caused more difficulties in the form of more failed trials. Because some older people could not lift the medium handle in the low friction condition, while all young participants managed it, it can be said that power grip becomes more quickly strenuous for older people.

The effects of object distance from user, object width, object surface friction, and people's age on the kinematics of people's pre-contact phase are listed and discussed in the section below.

7.4.2 Effects of Pan Handle Diameter, Friction, and Distance on Power Grip Reach-to-Grasp Kinematics

As expected the further the object is the more time is required to reach it and reach maximal hand velocity. Unlike pinch grips, power grips require low level of precision in finger positioning, which is thought to be the reason why people of all ages always reached their MGA at the same time across trials. Identically to pinch grip, people of all ages will reach higher hand speed with further objects. Distant objects allow better adjustment of grip aperture and evaluation of grasp, permitting people to minimise their grip aperture safety margin. Therefore once the object is reached less time is required to secure one's grip.

Younger adults appear to have a better adaptability to different handle sizes; a wider or thinner handle does not seem to require more time, hence concentration or attention from them. While similarly to pinch grip, older people increase their MT with object width. Unsurprisingly the power grip aperture formed by both age populations increases with the diameter of the handle to be grasped. Analogously to pinch grip, for wider handles people of all ages will give advantage to their grip aperture opening phase, spending more time to create a wider grip aperture. In addition young adults increase the time they spend to adjust their grip with wider handles. Whether it is for a pinch or a power grasp the width of and object is therefore an important factor dictating its accessibility and ease to grasp-and-lift.

Unlike for pinch grip, low friction did not cause a tremendous number of failures; enough data was collected to draw tenable conclusions. The physics of a power grasp makes the influence of surface friction less consequential than for pinch grasp. Nonetheless, friction was not expected to have so little effect on power grip reach-to-grasp. It only caused slightly higher peak speed on high friction, and longer opening time on low friction for young adults. Older people did not appear to change in any way their reach-to-grasp with varying surface friction. However low friction called for more hand slippage, hence more failures. An object with a more slippery surface is therefore more difficult to grasp and lift, and affects people's reach-to-grasp whether the users want to pinch or power grasp it. Nevertheless, the effects have tremendously greater consequences for pinch grips.

The absence of required precision and subtlety combined with a large contact area gives people confidence in their handling independently of the slipperiness of the pan handle. This conclusion results from the outcome of people's power grip on the medium and small handles. These handles were small enough to be entirely enclosed within a grip; it was thus difficult for it to slip out of grasp. Where in pinch grip gravitational forces are solely counteracted by frictional forces, in these power grips fingers could be placed underneath the handle offering a direct force in opposition. The theory on friction stipulates that stability us not dependent on the contact area, yet the addition of contact points in a power grip allow for the multiplication of patterns of grip force directions and orientations significantly reducing the importance of friction.

Older people took more time to reach the pans like they did with the small stimuli of Chapter 5. However, as discussed earlier they did not exhibit the same sequential motions. This shows a slower but more confident approach. Beside that, ageing only led older people to reach their peak speed significantly earlier than younger adults proportionally to their movement duration. They thus favoured a longer deceleration phase, sign of a more careful behaviour. Similarly to pinch grip, older people were observed to minimise their grip aperture, hence minimising their grip aperture margin. This is again certainly due to their lower hand dexterity making the formation of a grip aperture a more strenuous task for them. As the pans could not be knocked over this behaviour is not as unsafe as it was for the pinch grip tests. Less difference therefore appears between generations with power grasp, because lesser degrees of dexterity and precision are required.

Distance from the user, pan handle diameter, surface coefficient of friction, and users' age were the factors studied in this chapter but are not exclusive. The way people reach for a pan and their ability to successfully grasp and lift it is product and user dependent. When the handle becomes too large it can no longer be enclosed in the user's hand, then a power grip solely consists of a simple clamp. At this point rather than a power grip, the grip interaction resembles more to a pinch grip, where only the tip of the fingers applies a relevant force and where friction holds a large place. Consequently a too wide handle forces subjects to use a less powerful grip technique, which proved to be quickly insufficient, leading to the observed high rate of failures for the wide handle.

Finally, it must be reminded that the IRED markers were not, in this experiment, placed at the tip of both digits. This affected the absolute measures of MGA, but might also have affected the time to maximum grip aperture because the knuckles might have reached their MGA while the distal phalanges were still opening and even larger aperture. This supposition cannot be verified with the present data, but if it was to be true then MGA might have been reached later than measured. Placing the IRED markers at the tip of the two digits like in Chapter 5 could have resulted in larger absolute tMGA, however what tMGA really reflects is the grip aperture-opening rate and how it is affected by object properties and age. The effects of those properties on this opening rate are correctly reflected by the present tMGA measured in this chapter.

This chapter showed how reach-to-grasp for power grip on a kitchen pan is affected by product's handle size, surface friction, and location. Similarly to pinch grip wider handles and lower surface friction make the lifting task more strenuous, and can lead to inability to lift. However, in reasonable conditions, they have a lesser effect on people's action than in pinch grip. Age appears to have a smaller effect on people power grasp's pre-contact phase. It is hypothesised that when less precision and attention is required, people feel more in control and older people do not feel the need to have a too cautious approach. Older people exhibited behaviour more similar to young adults even if slightly more cautious, and yet young adults almost always performed 'stop-and-go' movements. This greater caution used by young adults indicates that older people, by being more experienced, felt more confident in a test close to an environment they are familiar with. Even if they are likely to struggle more when lifting a pan due to less grip force and hand dexterity, older people have acquired experience with time giving them great confidence and efficiency.

This chapter concludes a series of experiments and studies that have tried to map out the pre-contact and contact phases of a reach-to-grasp-and-lift movement for young and older adults. The next chapter brings together the findings of these experiments and discusses their implications for product design and future research.

Chapter 8

Conclusions and Further Work

Through every chapter this thesis has presented the research done in an attempt to better understand the repercussions of object properties and users' age on their reach-to-grasp movements and grip force. This chapter reviews the work of this thesis, discusses the findings of every study, and highlights the value of this research. It also discusses the limitations of this work, and area for future research.

8.1 Recapitulation

This section reports the outcomes of the work carried out in each chapter, and the discussions brought about by them. Chapter 1 posed the overarching research question, which was to frame the scope of this research:

"How do object size and surface friction affect young and older adults' reach-to-grasp motion and precision grip force?"

8.1.1 Chapter 2 – Literature Review

The research project developed upon this research question covers a wide range of domains that have been reviewed in Chapter 2. This literature review, in the first part, showed the growth of the ageing population over the last few decades, and the importance it has reached in developed countries' societies. In the second part, it revealed that although mindful design is developing and spreading in the form of inclusive design, few end products adapted to the general population are present. Indeed, with ageing, cognitive and physical deteriorations tend to arise, which can lead to impairments, major or minor. These impairments, which have predominantly been found to be lower force, stamina, tactile sensitivity, and dexterity together with deterioration of skin properties, are turned into disabilities by inadequate tools and environments. Although inclusive design is ever more present, a considerable amount of tool design processes go through without considering the older population. Following the growth of the ageing population, research on older people has been developing over the last few years, nonetheless much work needed to be done, and much work needs to be done still after this thesis. Chapter 2 highlights the importance of prehension in maintaining independent living and quality of life. The kitchen environment was taken as the context of this research, because it plays a large part in people's lives while requiring the achievement of complex tasks and use of a wide range of utensils.

The veil of differences in abilities between young and older adults is being progressively lifted, and the reasons for older people's struggle can partly be explained. Nevertheless, the effects of ageing on grasp abilities and their repercussions on prehension are not well documented. Prehension is one of the main methods of interaction between user and product, and literature does not thoroughly explain how product characteristics and ageing may influence people's reach-to-grasp actions. Since products' properties bear an important role in the interaction between the users and their environments, they can lead to loss of autonomy and deterioration of quality of life for those whose capabilities do not fit the norms typically assumed by designers, as can be the case with older people. There is no cure to ageing, but any product can be improved to become more user-friendly. The findings presented in this thesis are applied to products found in a kitchen environment, especially pans, yet they can be extended to a wide range of other handheld tools.

8.1.2 Chapter 3 – Methodology for Investigating the Influence of Ageing and Object Properties on Prehension

Precision and power grasp techniques comprise the great majority of all grasp variants. Pinch grip is preferred for precise movements and delicate grips on small and light objects, while power grip allows a larger and higher range of grip force combined with a higher stability. Both grasp techniques are used daily in cooking tasks, yet pinch grip has been favoured for the majority of this thesis' research because it stands as a basic grip, simpler to analyse and characterise. Furthermore, it stands on larger research documentation. Both grasps consist of an approach and a contact phase, involving targeting of finger placements and forces, and computation of many sensory inputs by the central nervous system. The same basic principles of physics underpin both grasps, but a large contact area makes the representation of grip fore distribution harder for power grasp. A larger hand surface in contact involves more force application points, more skin deformation, different degrees of tactile perception, and more force application directions.

Chapter 3 draws the force vectors in action during grasp, and the conditions for a secure grasp. It focuses on the tangential and normal forces defining the grip force, and on their relative proportions for a stable grip. The cone of friction generated by the friction between the skin and the object surface dictates the range of force magnitudes and directions that can be applied without slippage. Lower friction requires more precise grips and reduces the number of muscle coordination patterns for stable grasp. Wider grip aperture reduces the number of these patterns as well, which leads to the assumption that object friction and width would influence people's prehension.

The methodology followed throughout this thesis is detailed in Chapter 3. Many research questions were drawn from the overarching research question, and every one of them oriented the present research work. The methodology explains how every objective was tackled and why.

8.1.3 Chapter 4 – Focus Groups

The ultimate goal for research of this kind is to help older people remain independent and safeguard their quality of life. Older adults were thus the key to this work, and were therefore placed at the centre of this thesis' research. Therefore older people were given an active voice to express their needs, and what helps them to remain independent while retaining a good quality of life. Chapter 4 firstly reports this investigation run through semi-structured focus groups. These discussions revealed how food preparation holds a large part in people's life, but most importantly they revealed how individuals perceive the effects that healthy ageing's subtle changes have on their performances. Chapter 4 also showed the general and individual cooking and eating habits' evolutions with time, together with an estimate of older people's dexterity and behaviour in the kitchen. This study helped to refine the research questions tackled in this work.

Chapter 4 revealed that the older people surveyed agreed on the importance of good grasp capacities necessary for efficient, safe, and accurate handling of kitchen tools. They are aware that age brought weaknesses onto them making hazardous tasks more delicate and dangerous. They report that dexterity in wrist and shoulder, and hand strength have suffered significant deterioration with ageing. However some stipulate that more than impairments, age gave them experience, and they have learned to be more cautious in what they do. For them being more cautious involves doing things more slowly, thinking through every task, and planning eventualities such as finding yourself carrying a hot plate without having any area freed to place it.

In short, independent living and good quality of life partly come from easy handling of kitchen utensils. This results from good fluidity in reach-to-grasp and accurate grip force application, which ageing seems to be significantly affecting.

8.1.4 Chapter 5 – Pinch Grip Reach-to-grasp in Older People

Handling an object does not solely consist of maintaining a grasp. It follows an approach phase, referred to in this thesis as the reach-to-grasp pre-contact phase, during which people are forming their grip and estimating object properties. Chapter 5 builds on the literature to detail the influences of object size, friction, and distance from user on precision grip reach-to-grasp for young and older adults. Many object properties are likely to affect prehension, but size and surface coefficient of friction are thought to be the most influential factors.

Low friction objects are more difficult to grasp and handle, people have thus to increase their movement time, and spend more time securing and adjusting their grip. Increasing the distance at which an object is placed increases the grip aperture sizing and timing, the duration of the reach-to-grasp movement, as well as its velocity. Distant objects allow more space and as a consequence more comfort; people feel more secure and opt for a shorter aperture-closing phase. As the object widens then a larger finger grip aperture is to be formed if the object is to be grasped. As a result more time is necessary to reach maximal grip aperture, and the opening phase thus grows in importance during approach regardless of the dexterity and age of the person. As with lower friction, wider objects force a slower approach, increase the likelihood of using a 'stop-and-go' motion, and a longer period to secure one's grip. As a consequence, object width is, like surface friction, an important factor dictating the accessibility of an object; wide objects are more difficult to successfully grasp.

Older people almost exclusively perform 'stop-and-go' movements regardless of the object friction. To observe such a high proportion of 'stop-and-go' actions with young adults the object's surface has to be slippery. Old age generates slower reach-to-grasp actions, coupled with a large deceleration and aperture-closing phase, more time is required to reach maximal grip aperture, peak speed, ultimately the object, and to secure one's grip. Furthermore, for the older population the hand is decelerating for more control through most of the approach, and predominantly stops in its motion to secure a grip. These characteristics emanate from a cautious behaviour where attention is taken through every step, or from a greater difficulty in performing the task. Age turns any reach-to-grasp situation in a more difficult task, which provokes a more cautious approach. In addition, age generally reduces finger dexterity impeding grip aperture formation, and thus limiting grip aperture's safety margin, making collision with the object more likely. Older people by minimising their effort, amplify the risk, which explains that even tough they take more care they do not have the success rate of young adults.

Cambridge Impairment Simulator Gloves (CISG) were tested for the first time in Chapter 5 with their effects on reach-to-grasp. They showed that lower hand dexterity forced young adults into being more careful in their reach-to-grasp, and in adopting behaviour similar to older adults. This proves that low hand dexterity plays a large part in older people's behaviour. In terms of grip aperture sizing and timing, as well as hand velocity, CISG are a good tool to replicate old age and suggest that a large part of older people's reach-to-grasp is due to their lower dexterity. Yet hand dexterity subtly decreases with time while the gloves bring a sudden drastic change. Unlike older people, young people do not have the time to adapt to the condition caused by CISG. This has great repercussions on people's handling and collision avoidance success. Young adults wearing the gloves did not shift towards a 'stop-and-go' strategy, and consequently had more drops. Abrupt changes in capability do not reflect the motor learning that can compensate for it.

8.1.5 Chapter 6 – Pinch Grip Force in Older People

Chapter 6 demonstrates that object size and surface friction, not only have an effect on reach-to-grasp, but also on the maximum grip force that can be applied during a grasp. Grip force defines handling, and the stability of the grasp, and it is reduced on low friction and wide objects. Friction reduces people's grip force capacities, but it also reduces the grip they use to lift objects as well as their slip force. Its effect is constant across different widths. Grip force capacities drastically drop once the object width is closing in on people's maximal grip aperture.

Unlike for reach-to-grasp motion, age and loss of dexterity proved here to have no significant effect on people's grip force capacities and use, or no interaction with any of the product properties tested. Such findings were not expected as older people are presumed to have lower grip force (Mathiowetz et al., 1985; Werle et al., 2009). However, looking in more details at the results of Mathiowetz et al. and Werle et al., the decrease in grip force is mostly observed on power grip, and not so much on pinch grip. Chapter 6's average age was of 28 for the young cohort and 69 for the older cohort. In both normative studies the difference in pinch grip force between the 25-30 and the 65-70 is on average 775 g. Also, Werle et al. observed high grip force variation with people aged 70 and older, and these variations were due to high differences in people's activity level. Additionally, pensioners who do not need help for their daily activities have 54% higher pinch grip force, than those who do (Werle et al., 2009). As a result, active people, belonging to the healthy aged population, can still present good grip force even at 70. Age was not found to be influential, because Chapter 6's tests were done on pinch grip and with healthy older people mostly between 60 and 70 years old. Nonetheless, there was an interaction between the width to be pinched and people's age on the number of time the object unintentionally slipped out of grasp. Thus reflecting a greater increase in difficulty for older adults as the object got wider.

Finally, when expecting a sudden and unpredictable perturbation in the form of the addition of an inertial load stopping the object in its course, people apply a large grip force safety margin in order to be able to cope and keep hold of the object.

8.1.6 Chapter 7 – A Power Grip Reach-to-Grasp Approach in Older Adults

With a good understanding of the influence of object properties and age on reach-to-grasp movement and grip force during pinch grip, their influences on reach-to-grasp were evaluated during power grip. As before, the effects of object size, friction, and distance were studied in Chapter 7. In an attempt to bridge the gap between daily living and laboratory investigations, kitchen pans were used as stimuli.

By observing the same metrics as for the pinch grip, it was demonstrated that people are more successful and much quicker in power grip reach-to-grasp. It was observed that the coefficient of friction of the pan handles had no significant effect on reach-to-grasp actions, whereas their diameter had a tremendous effect. Additionally, findings showed that similarly to pinch grip the duration of the reach-to-grasp approach as well as hand velocity were scaled to object distance. As a consequence it can be said that regardless of the grip technique an object gives rise to, the further it is placed from the users the longer it will take to be reached, even though higher hand velocities are used. Finally, age has a smaller effect on reach-to-grasp for power grasps than it has for pinch grasps. Older people are slower and take more time to reach-to-grasp, yet oppositely to pinch grip they exhibit less 'stop-and-go' motions than young adults do.

8.2 Research Contribution

This thesis has investigated the effects of object size, surface friction, and ageing on reach-to-grasp movements and grip forces. Before doing so, it gave an active voice to older people to collect their perspective on what causes the most difficulties while using utensils to prepare food in their kitchen.

The focus groups described in Chapter 4 demonstrated the importance of cooking and eating in daily life for older adults. From their perspective, older people admit that they need more time to do things. Their global observation is that they are more cautious, and therefore do things more slowly, and put a lot of attention in what they do. They admit that accidents can have greater impact on them; therefore any hazard can have disproportionate consequences on them. They are at higher risk, life has taught them patience, and accumulation of accidents and injuries through the years has taught them caution. In addition, they admit that they have slower reactions, and lower physical abilities, principally lower strength. This perceived lower force does not tally with the findings, because the present grip force findings were obtained for pinch grip, while people referred mostly to their power grip force capacities. As explained earlier pinch grip force is less affected by age than power grip. Additionally, it is hypothesised that lower force becomes more evident on heavy objects and prolonged grasp (i.e., the ability to maintain a hard grip), which is what people experience while cooking. They encounter more difficulty cooking and preparing food than they used to because of that lower strength, but also because they get tired more quickly, feel pain in certain parts of their body, or because they lack dexterity. However, they have found adaptations over the years to get around the limitations that ageing brought. Those adaptations have become part of their daily life, and they do not even realise that they use them anymore. It is therefore quite difficult to distinguish what ageing forced them into, what part of their behaviour is due to experience and what part is due to impairments.

The older adults questioned rely on many different kitchen utensils and appliances; their use is really individual specific, but they all use the same basic equipment, which are pans and knives. Furthermore, these basic tools are the ones they want being improved, and adapted. They do not fancy all the gadgets that have been put on the market supposedly to facilitate such or such task, but they aspire to find pans that are convenient, good quality, easy to use, and light to lift. A pan is a very important utensil for the majority of older people, yet none of them have found one matching all their requirements. There is thus an evident gap in the market, which reveals how kitchen utensils designers are disconnected from older users. If designers ignore so much what the ageing population needs and desires, it is because so little is known about them, and the present work is one more step towards filling this gap. Older people try to match the products they buy to their abilities, taste, and finances; therefore products must be attractive, inexpensive, and adapted without any negative connotation.

The above provided the grounding putting this research into a real-world context, while the area of academic novelty in this research was defined by answering the four research questions set out in Chapter 1. The investigations on the interaction between products and users, inspecting the effects of object size, friction, and location on people's reach-to-grasp actions led to valuable knowledge for handheld tool designers. This section reviews the answers to each of the research questions in turn.

RQ.1 – ***Does age affect the way individuals adapt their reach-to-grasp movements to changes in object size and friction?***

Previous research has demonstrated that object properties such as size and surface friction as well as object location have significant influences on the structure of people's reach-to-grasp actions. Slippery and wide objects are more difficult to grasp and therefore occasion more failed attempts; people adapt their reach-to-grasp action in consequence. The present work detailed how young and older adults adapt their reach-to-grasp behaviour to object width, friction, and location. Most importantly wider and more slippery objects are more difficult to pinch grip and lift, they therefore generate slower and more cautious reach-to-grasp. Older people adopt a slower reach-to-grasp, and predominantly stop it to secure their grip. Such conduct could well be due to greater caution because of greater difficulty, in the case where demands and capabilities mismatch. But does there need to be more difficulty for older adults to be more cautious? Chapter 5's experiment proved that regardless of the object's surface friction older adults predominantly sequenced their approach, while the high friction condition did not present great difficulty. It is difficult to know for certain whether older people experienced less difficulty with the high friction condition, but it seems that older people are also more cautious than young adults even where they do not seem to experience difficulty. The outcomes of Cambridge Impairment Simulator Gloves tests showed that more caution was used for more difficult tasks. Young adults had to adopt a transport phase similar to older adults, a more cautious approach, in order to cope with the increased difficulty caused by the reduction of their dexterity. Their low finger dexterity limits their grip aperture formation abilities, as a result they minimise grip aperture margin while increasing the risk of hitting the object, similarly to older adults.

RQ.2 – ***Does age affect the way object size and friction limit the maximum force that individuals can apply to a given object?***

Interestingly pinch grip force capacities do not vary with age and hand dexterity. However, as the object widens, maximum grip force plateaus around a peak value for small and medium objects, but then drastically drops once the object becomes larger than half of the size of users' hand. The object becomes then almost impossible to grasp and lift. An object, whose width sits within the peak plateau region, can more easily be lifted (depending on its weight). The force used to grasp and lift it does not fluctuate with width. However, for objects of a width larger than this region, little grip force can be applied and little force direction patterns are achievable; the frictional forces are no longer large enough to prevent slip. Stably grasping and lifting these objects becomes more difficult. Lower object surface friction lowers people's grip force capacities similarly across all object widths. Consequently the range of widths that can be stably grasped and lifted is thus reduced in low friction conditions, because the point at which frictional forces become too small to prevent slip occurs on smaller objects. Object width and friction therefore dictate the easiness of a grasp, hence the accessibility of a product.

During brusque and short lifting motions of an object stopped unpredictably, the grip force used is largely greater than the force required to hold the object still in the air, or even gently move it around, where people have time to stabilise their grip. People, when aware that a shock will occur during their handling motion, use a large grip force safety margin to make sure the object does not slip out of their grasp. Although literature has demonstrated that for gentle handling actions grip force is inversely scaled to friction (Cadoret

& Smith, 1996; Cole & Johansson, 1993; Edin et al., 1992; Flanagan, J. Randall & Wing, Alan M, 1997; Gilles & Wing, 2003; Johansson, 1996; Johansson & Westling, 1984; Westling & Johansson, 1984), the present research revealed that it is rather the opposite for maximal pinch grip, and peak lift force. Similarly to the static pinch grips, the maximal force used to cope with a sudden perturbation during lift is lower on lower friction objects. Unlike the literature stated above, where the low friction condition is represented by textures such as suede, or smooth glass, the present research has brushed Vaseline on the objects surface generating a low friction condition drastically more slippery. It caused great grasp instability. However, this thesis has also shown that this research is not the only one (Engel et al., 2010) observing lower grip force for lower friction. It is though believed that people applied a lower force on slippery objects by fear of thrusting it out of grasp, or because it required more precise muscle coordination.

Interestingly no age effect was observed and it can be considered that older adults are as capable of producing a grip force as young adults. Yet, the older cohort was predominantly constituted of women, yet so is the older population. Women are known to have less grip force than men at any age (Mathiowetz et al., 1985; Werle et al., 2009; Yoxall et al., 2008), as a consequence it can be hypothesised that the average pinch grip force over the entire cohort is lower than it should have been if the age group had been constituted of an even distribution of men and women. Our findings contradicted previous research findings such as Gilles and Cole's (Cole et al., 1999; Gilles & Wing, 2003). However, research is not unanimous on that latter point. Similarly to the present research, Gilles and Wing measured constant safety margins across ages, whereas Cole et al observed older people's safety margins being twice as large as the ones of young adults.

RQ.3 – ***In what ways, if any, do impairment simulation gloves replicate these effects?***

Because it was hypothesised that hand dexterity holds a major part in older people's reach-to-grasp actions and grip force application, CISG were thought to be a good simulator of old age in terms of hand grasp. Chapter 5's outcomes revealed that young adults adopted a reach-to-grasp approach similar to older people when wearing the impairment gloves (i.e., slow pace and low MGA). Whilst Chapter 6 demonstrated no difference in grip force capacities with ageing, and unsurprisingly no differences with CISG.

CISG do not force young adults to have reach-to-grasp actions identical to older people. CISG do not force people into more 'stop-and-go' reach-to-grasp approaches unlike ageing. Additionally, the dexterity impairment generated by CISG causes many failures, because it is important and sudden. Ageing brings a subtler, more gradual dexterity impairment. People's clumsiness with CISG reflects that they are not well accustomed to the gloves, and are tempted to behave as they always have even if the gloves are reducing their dexterity. The main characteristics of ageing that CISG cannot replicate are habits and experience. Older people have learned to live with their condition, while young adults did not have the time to get used to their sudden loss of dexterity.

Nevertheless, the tests done with CISG prove that low hand dexterity and age influence reach-to-grasp in similar ways. It can therefore be hypothesised that the slower pace of older adults, their lower grip aperture margin, as well as their long deceleration phase are likely to be predominantly due to their lower hand dexterity. Lower dexterity decreases accuracy, and more care and time must be taken to secure one's grip. Age and loss of dexterity do not affect grip force, but have similar effects on a person's reach-to-grasp, lowering an object's accessibility. Loss of dexterity impedes grip formation and precise adjustments, and consequently reduces sensitivity; it can limit the contact area or induce pain. Loss of tactile sensitivity and kinaesthesia also impede the information analysed by the CNS, and consequently the efferent signals sent by the CNS to the hand. Therefore by lowering sensitivity, dexterity reduces the accuracy of the CNS adjustments, which in turn reduces the quality of the grasp even further. This gives rise to difficulties in applying effectively a stable grasp, as seen with the participants wearing CISG. Even if they do not perfectly replicate an older hand, especially because they do not come with the experience and habits that ageing brings, CISG are an efficient tool to estimate age effects on one's hand. They also demonstrate that age brings impairments as well as experience, and older people's behaviour is the results of physical abilities combined with careful intentions.

RQ.4 – ***Do the influence of object size, object friction and age on reach-to-grasp actions with a pinch grip generalise to those using a power grip?***

Most human grip techniques can be considered as a subcategory of power or precision grip. Power grips allow larger force application and stability, and for that it is a more reliable and secure grip. For that reason and the fact that less precision is required the surface coefficient of friction has little effect on reach-to-grasp actions for power grip. The product property that dictates the action is the width of the product to be grasped. The present research demonstrates that when little precision and attention are required, less difference is noticeable between generations. Nonetheless, reach-to-grasp slows down with age regardless of the grasp technique. Moreover, oppositely to pinch grip, by having far less 'stop-and-go' approaches than their younger counterparts, older people seem to show more confidence. Age develops experience and practice in realistic cooking situations, both benefit older people, allowing them rapid yet efficient handling.

8.3 Limitations of the Study and Suggestions for Future Research

Any study, any research one can undertake, can always be improved, refined, taken further. The present work is no exception. The limitations exiting in this work are detailed in this section. From those and from the observations gathered along all the studies run, guidance and suggestions for further research is also presented here.

Populations Sampled

Through the course of this thesis' research, two distinct populations were investigated: young and older adults. The young adult population was represented by cohorts constituted of students between the ages of 20 to 40 years old. The older adults population was represented by cohorts constituted of people over 60, who were members of the University of the Third Age or Age UK.

Firstly, the age brackets do not cover the entire human population. The age difference between the two groups studied was maximised to maximise the chances of observing a difference in behaviour. Findings have sketched reach-to-grasp actions for people at both ends of adult lifespan in the UK. It would be instructive to investigate the entire human lifespan to sketch the evolution through life of reach-to-grasp. A global study would highlight whether the changes occur rapidly, and to what degree, their onset and rate of change varies between individuals. Observing this evolution over the course of life could indicate possible explanations for the evolution of people's reach-to-grasp. Normative data on grip force over lifespan show how grip force gradually increases until a certain age and drastically drops at another point in life. A comparison with the evolution of reach-to-grasp over the lifespan would be most useful as it could suggest whether reach-to-grasp actions follow the same evolution as grip force. This could possibly suggest a correlation between the two. Additionally, from a product design point of view, such data could inform on the age at width people would start to struggle for a given design.

Secondly, each age group investigated in this research belonged to a specific group of the general population. The young cohorts were predominantly composed of students recruited within the University of Leeds, and the older cohorts were exclusively composed of members of two organisations providing activities for the older population. The first one is thus a very specific part of the young adult population, while the second one sampled older people who are motivated and sufficiently active to regularly take part in social activities. This thesis focused on the effects of healthy ageing, hence the recruitment of active older people. Nonetheless, sessions could be organised with older adults who have been more affected by ageing, and therefore suffer from lower abilities. Would they exhibit different reach-to-grasp or use different grip force, or even consider that age has had more effect on their cooking habits than society, technology, or significant lifestyle changes? Cultural and socioeconomic characteristics influence people's hand grip strength (Chilima & Ismail, 2001; Henneberg et al., 2001; Henneberg et al., 1998; Koley et al., 2009), they are therefore likely to influence reach-to-grasp actions and pinch grip force during a perturbed lift. A broader cultural, occupational, and socioeconomic range of people could be investigated to improve the generalisability of the findings, and gather data on people with different habits, capacities, and lifestyles.

Lastly, the older participants who volunteered for the experiments were mostly women. There is nonetheless value in undertaking this thesis' studies with a skewed sample, because the proportion of older women in the global population is skewed. There are indeed more older women then older men due to their longer life expectancy. This high proportion of women is however thought to have a repercussion on the outcomes of this thesis, because women are reported to have lower grip force. The effect of gender should be verified in further research by running the tests with an older population evenly distributed between the two genders.

Handheld Tools

Every aspect of this thesis research was developed with the spectrum of applying the findings to a kitchen environment, and improving kitchen tools. This point was most evident in the focus groups and the power grip reach-to-grasp experiment, where wok pans were used as stimuli. This research opted to investigate kitchen tools handling because cooking is thought to be the most influential factor on independent living and good quality of life. Nevertheless, on a daily basis people manipulate a wide range of handheld tools not necessarily cooking related. Further research could be developed to extend this research's scope to a wider range of handheld tools, even though the present findings are suspected to be largely extendable to the majority of handheld tools. An interesting point had been raised in Chapter 6: would the findings be similar on fragile objects, objects that if squeezed too hard would break? It would be interesting to extend the reach-to-grasp analysis of Chapter 5, and the force measurements of Chapter 6 to a range of more fragile objects. In the presented studies objects were made of Nylon, and could not be damaged in any way. It is believed that reach-to-grasp actions, and the grip forces applied on the object if it was made out of a more fragile material would be significantly different from the ones observed in this thesis. Profitable knowledge would be gained if future research were done on grasp on breakable, fragile objects, or objects made out of yielding materials, because they have not been intensively researched.

Cambridge Impairment Simulator Gloves

In Chapter 5, the findings indicated that Cambridge Impairment Simulator Gloves bridge the gap between young adults and older adults' abilities, with the inconvenience that they do not reflect the motor learning that is acquired with age. Subjects by not being used to the gloves did not completely change their behaviour, or entirely adapt to the alien objects. The findings thus gave birth to the hypothesis that if subjects were to wear the gloves over a longer period of time prior to the experiment, maybe their reach-to-grasp would match even more closely the one of older adults. Such a study has its limitations, since it would be demanding to have people use CISG for a longer period, and verify that they thoroughly do it. What would be the outcomes of an inclusive design process relying on CISG to evaluate the struggle generated by a product on low dexterity hands? The reduction of dexterity is significant with CISG, and people are unlikely to be used to such equipment and condition. As observed, CISG make its users extremely clumsy, but even if this clumsiness is taken to such extremes that it overtakes older people's it does not make the design observations useless. As a matter of fact, because the impairment against which the design is evaluated is great (greater than the impairment developed with healthy ageing), it will be even more inclusive. However, in trying to match the design to be perfectly confortable even with CISG on, there is a risk of overcompensating. As long as designers take care not to end up designing unattractive products, then CISG are an effective tool for inclusive design evaluation.

Finally, CISG were noted, in Chapter 6 to have no effect on pinch grip force capacities. Because they hinder the formation of a fist, there is a probability that if smaller objects were to be tested then maybe the resistance the gloves offer to finger flexion would significantly affect people's grip force capacities. CISG were developed to considerably lower someone's hand dexterity and thus simulate arthritis, it would therefore be intriguing to compare their effect with people suffering arthritis.

Set-up and Protocol Improvements for Grip Force Measures

Running experiments with the set-up and protocol in place brought to light some possible improvements. As a matter of fact, the apparatus used in Chapter 6 could be improved with the implementation of tools inspired from Westling and Johansson's work (Westling & Johansson, 1984). They embedded two sets of strain gauges to measure not only the grip force but also the vertical load force. They also used a light-position sensitive photoresistor mounted in a camera sensing the position of an infrared light emitting diode fixed to the object. With such equipment the position of the object can be recorded, and therefore the course of the object during lift can be monitored with the effects on motion of the perturbation. In addition, by drawing the course of the object, it can provide the precise instant when the object is dropped for a more precise reading of slip force. Replacing the dynamic Dytran force transducer by a static force transducer, which would not discharge during constant load application, would make the Honeywell load cell obsolete. Removing the Honeywell from the stimuli would allow the removal of the extruded cut at one end of the cylinder, potentially affecting grip or tactile perception. This would also offer a better grip surface to both fingers. Lastly, this research taught us that imposing low grip releasing speed to participants, results in slower more gradual decreases of grip force for more accurate readings. Additionally, before releasing the object, a phase, where the object is simply held still in the air, should always be added to let the grip force stabilise to the level participants feel comfortable with to handle the object. This value can then be used as a threshold to compare both peak and slip forces.

All these improvements, if implemented to the grip force experiment would result in more accurate readings of grip force, load force, and slip force, while generating readings for the course of the object. It should also provide more information on the grip force used to hold the object, and not solely used to cope with a sudden stop in the movement.

Power Grip Forces Distribution on a Kitchen Pan

Although grip force capacities and reach-to-grasp actions have both been studied in this thesis for pinch grips, for power grips only reach-to-grasp was studied. This thesis' research could be completed by a study on the evolution and distribution of grip force during a perturbed lift of a kitchen pan. However, measuring the forces in action and their distribution over the contact area is significantly more tedious in a power grip than in a pinch grip. Grip force is distributed unevenly across the palm and fingers. Researchers have tried to study grip force when cylindrical objects are grasped within one's hand. Though due to the complexity of the data collection, complex and expensive setups were developed, which still remained with important limitations. The research presented in this work represents an optimal use of the limited resources allocated to this project given the time available. If such non-trivial setup had been developed less studies and outcomes could have been achieved.

In the case where an affordable and efficient way of measuring power grip force distribution could be adapted to cylinders of varying diameters and surface friction, further research should be developed in an attempt to extend the pinch grip force data obtained in this thesis to power grasp situations.

Handling Energy Demands

From the global observations of the outcomes of this thesis a new question arose: Is handling more energy demanding for older adults? In the research domain of affordances the effect of given designs on people's energy consumption is an important factor (Warren, 1984). This thesis revealed how age affects people's handling, especially their reach-to-grasp actions. Older adults are more careful, take more time, and try to compensate for lower grip force capacities and hand dexterity. It was observed that they are less efficient and successful than younger adults, and it would be interesting to see whether the handling tasks are more energy demanding, and more exhausting for them. Such question could be answered in future work by performing handling tasks during which the heart rate or oxygen consumption of people of different ages would be measured.

Object Properties

Finally, throughout the course of this thesis research has focused on object surface friction and object width as properties influencing one's reach-to-grasp actions and grip force. They have been selected because they have a significant influence on both aspects. However, the effects on forces application during grasp of other object properties such as temperature (Carnahan et al., 2001), or weight (Westling & Johansson, 1984) suggest that they most certainly must also have an influence on reach-to-grasp. Additionally, object properties such as stability (Mon-Williams & Bingham, 2011), and shape (Sartori et al., 2011) have already been shown to affect reach-to-grasp, but could be investigated further by studying their combined effects on different age groups. Further research could therefore be run to investigate a wider set of object properties likely to affect people's handling. A product is the combination of many properties, and understanding the effects of each one of them for different age populations can only lead to better designs for everyone. The combination of this thesis' research with these research suggestions will lead to design guidelines for a wide range of handheld tools, making more products more accessible to the global population, and especially the older users.

8.4 Conclusions

The human body and mind can work together to adapt and confront developing weaknesses, but ageing is unavoidable, capacities will be lost. Handling is affected because hand dexterity, reactivity, grip force, and skin properties wane. Older adults confessed that even if they might do what they can to fight it, ageing makes environment interactions more laborious.

This thesis has shown how older people adopt a reach-to-grasp technique different from younger adults, while maintaining equivalent grip force capacities. These variations in handling are partly due to conscious care that older adults put in everything they do, and partly to lower capacities, especially their lower dexterity in hand and fingers. Age therefore forces people in being slower, and more cautious without compensating for the struggle they face while handling handheld tools. While product designers cannot stop a person from ageing, they can improve products by arranging its properties to make them accessible to the widest population. This research has demonstrated how product properties such as size and surface friction considerably affect people's reach-to-grasp and grip force capacities.

The findings of this research do not have to be limited to kitchen pans, they can be extended to the whole kitchen environment and even further; they inform on pinch and power grasp encompassing all handheld tools. Future work should concentrate on investigating the effects of a wider range of product properties. This can be supported by developing the research to measure the effort older people put in handling. The ever-growing older population gives space to an ever-growing need for further research.

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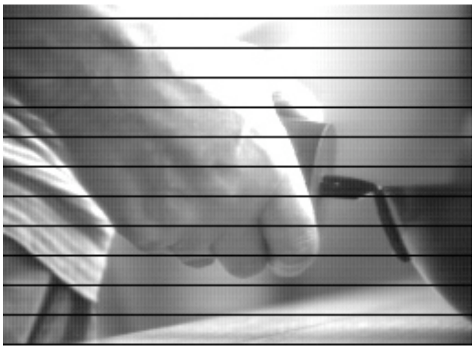
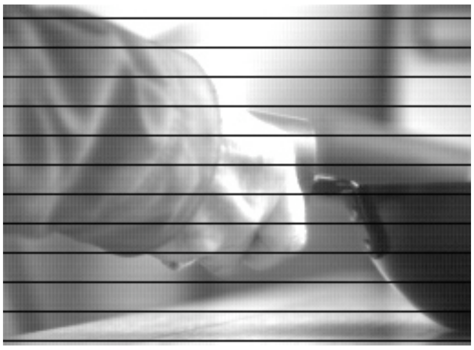
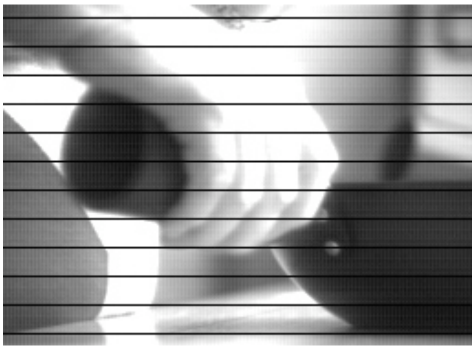
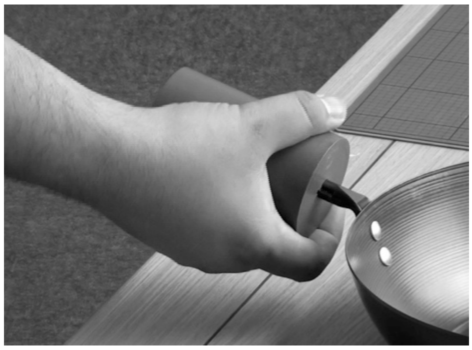
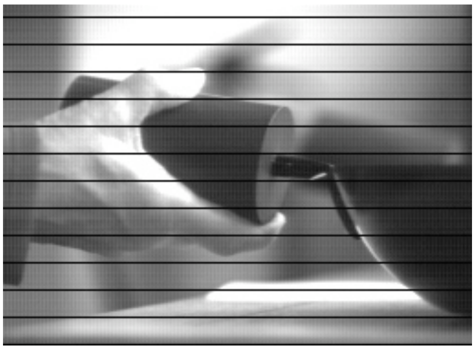
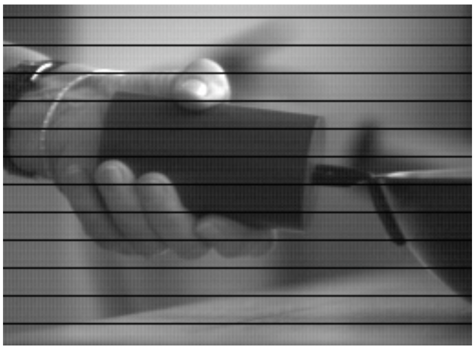
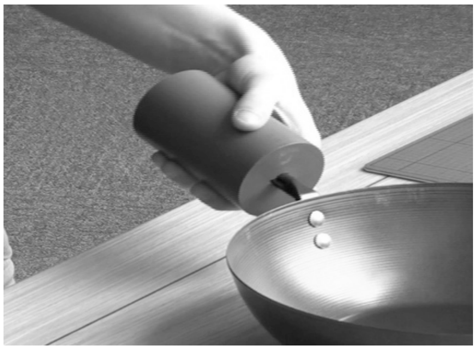
Appendices

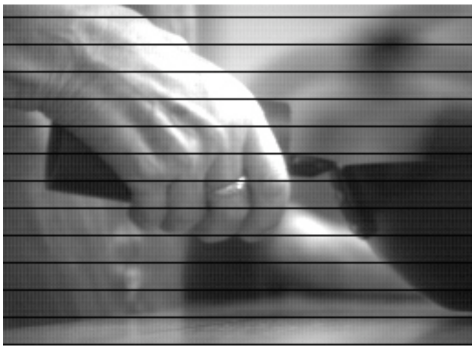
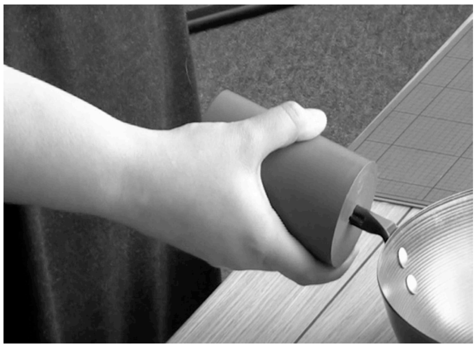
Appendix 1: High-Speed Video power grasp capture

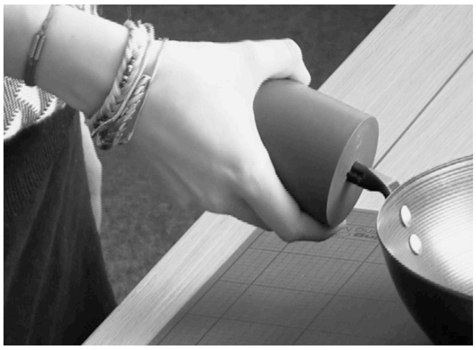
As a mean to observe how younger and older adults grasp a pan with a 60 mm diameter, HSV recordings were obtained in **Chapter 4**. Those recordings were used in the construction of the power grasp protocol of **Chapter 7**. Photo captures taken from the HSV camera of all the young and older participants are presented in this appendix.

Older people	Young people
	
	

Older people	Young people
	
	
	
	

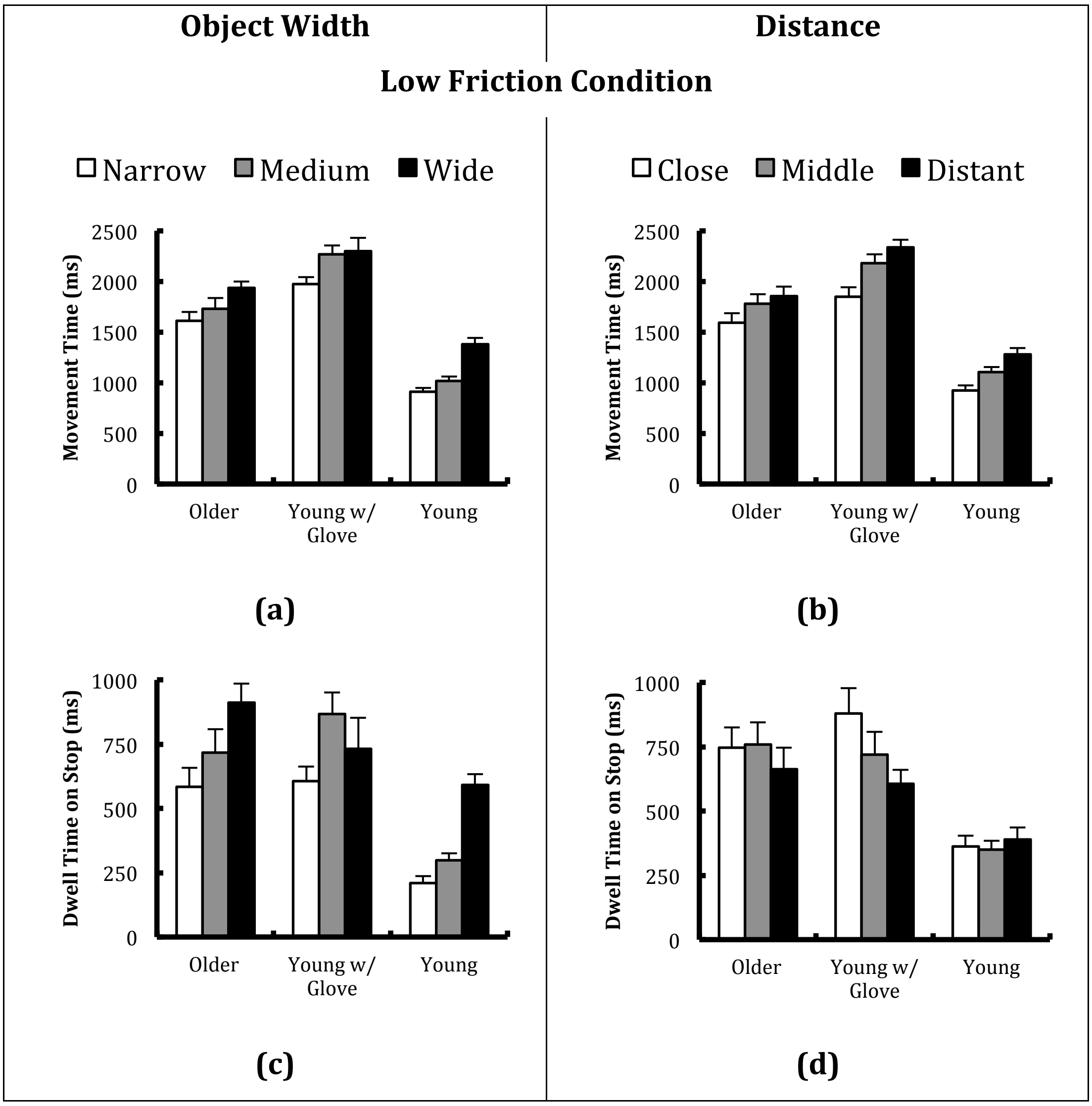
Older people	Young people
	
	
	
	

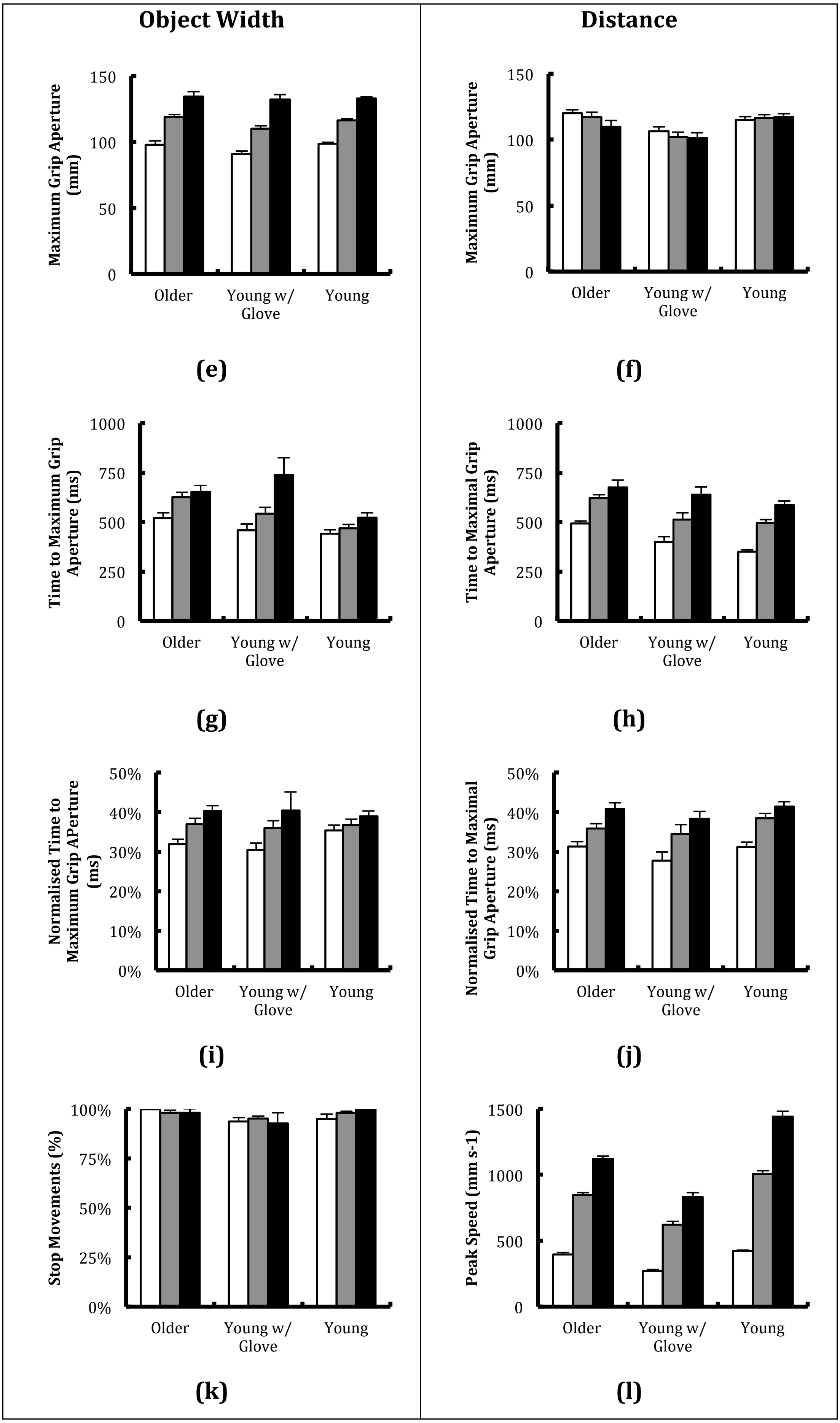
Older people	Young people
	
	
	
	

Older people	Young people
	
	

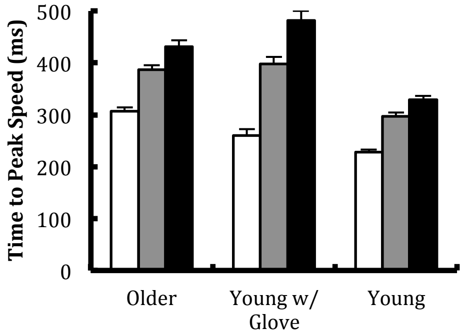
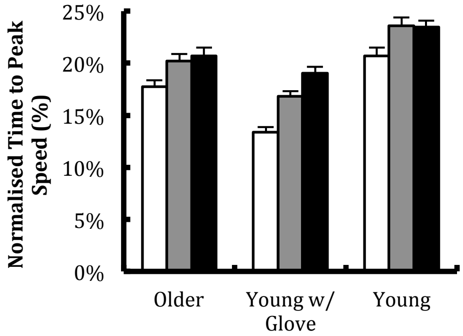
Appendix 2: Average kinematic values for each participant group grouped by object distance or object width in the low friction condition for pinch grip reach-to-grasp

During the pinch grip reach-to-grasp the rate of failures of older and gloved participants resulted in little reading in the low friction condition preventing any tenable statistical analysis. The speculations done on possible significant effects of object width, and distance from user were reported in **Chapter 5**. This appendix reports the evolution of all the average kinematic values for each participant group with object width and distance in the low friction condition for pinch grip reach-to-grasp.





Object Width
Distance
Maximum Grip Aperture (mm)
150
100
50
0
Older
Young w/ Glove
Young
(e)
(f)
Time to Maximum Grip Aperture (ms)
Time to Maximal Grip Aperture (ms)
1000
750
500
250
0
(g)
(h)
Normalised Time to Maximum Grip APerture (ms)
Normalised Time to Maximal Grip Aperture (ms)
50%
40%
30%
20%
10%
0%
(i)
(j)
Stop Movements (%)
100%
75%
50%
25%
0%
Peak Speed (mm s-1)
1500
1000
500
0
(k)
(l)

Object Width	Distance
	 **(m)**  **(n)**