Grasping Changes in Healthy Older Adults: Adaptations in Motor Control

William Shaw

Submitted in accordance with the requirements for the degree of Doctor of Philosophy

The University of Leeds

School of Biomedical Sciences

June 2020

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.

Acknowledgements

Many people have supported me through this PhD process. First of all, I would like to thank all of my supervisory team. Dr Sarah Astill, five and a half years is a long time to put up with me – thank you for all of your guidance, support and everything you have taught me. Dr Rachel Coats, Dr Ronaldo Ichiyama, Dr Ioannis Delis, Dr Ray Holt – I've been blessed to have such a diverse team spread across engineering, motor control, psychology and neuroscience. You've all been so understanding and supportive during this journey. A huge thanks must also go to Brendan McDermott, although not officially down as a supervisor, your technical support and exceptional electrical engineering helped bring this project to life.

A big thanks must also go to all of the participants who took part in this project. From undergraduates to octogenarians – it was wonderful to meet you all and hear about your experiences of the world. Adie, Bethan and Una thank you for your assistance in recruitment and data collection as part of your dissertation projects. I sure hope it was a useful experience as you transition into working life and postgraduate study. To my office friend turned Doctor, Dr Antonio Capozio, it was great to share this journey with you.

Thank you to my wonderful girlfriend Maisie. I'm sorry for all of the late nights and weekends of work. You've been ever so understanding and have always been so supportive. Many thanks also to my cousin Jon, who helped me during data collection in Suffolk and gave himself the self-proclaimed title of 'Junior Data Scientist'. Last of all, many thanks to my Mum and Dad who will be very proud, even though they still don't understand what a PhD is, or why anyone would choose to do one.

Abstract

With advanced age comes decline in motor function, including a reduced capacity to perform activities of daily living (ADL) such as cooking, eating and dressing. The ability to grasp and manipulate objects forms an integral part of performing ADL, with some tasks requiring one hand (unimanual) and other tasks requiring the coordinated use of both hands (bimanual), however both unimanual and bimanual grasping are affected as a result of ageing. The aim of this thesis was to better understand changes in unimanual and bimanual grasping in older adults (OA) and how these changes relate to reduced manual dexterity observed in OA. The first experiment documents the building of a portable, bimanual manipulandum system that can be used to assess grasping in OA. The second experiment explored differences in unimanual and bimanual grasping between younger adults and OA using a grasp-lift-replace paradigm. The results show OA exhibit: i) slower grasping strategies with higher levels of grip force, ii) reduced anticipatory control and iii) changes in distal, upper-limb muscle activation patterns during initial stages of the grasp and lift. These changes were apparent across unimanual and bimanual grasping tasks. In experiment three OA were stratified into subgroups displaying good and poor levels of manual dexterity. Results from the grasp-lift-replace paradigm found that both OA groups showed slower lifting strategies and elevated grip force profiles compared to younger adults. However, measures of reduced anticipatory control were the only statistically significant ($p < 0.05$) grasping variables separating OA groups with good and poor levels of manual dexterity. Changes in distal, upper-limb muscle activation patterns were also evident within the OA group exhibiting poor levels of manual dexterity. The findings from this thesis demonstrate OA show slower, more cautious grasping strategies, but these changes are not indicative of reduced manual dexterity. Age-related decline in manual dexterity is better explained by reduced levels of anticipatory control, that may be a result of changes to underlying muscle activation patterns during grasping.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ΔGF	Change in grip force
ΔLF	Change in load force
ADL	Activities of daily living
Ant Del	Anterior deltoid
ANOVA	Analysis of variance
APB	Abductor pollicis brevis
A_Y	Acceleration in the superior / inferior directions
A_Z	Acceleration in the sagittal plane
BM	Bimanual
CNS	Central nervous system
CoF	Coefficient of friction
D	Dominant hand
EMG	Electromyography
ECR	Extensor carpi radialis
FCR	Flexor carpi radialis
fMRI	Functional magnetic resonance imaging
G	Gravity
GF	Grip force
GF:LF	Grip force to load force ratio
H	Heavy mass
L	Light mass
LF	Load force
OA	Older adults
OA G	Older adults with good levels of manual dexterity
OA P	Older adults with poor levels of manual dexterity
MS	Muscle synergy
ND	Non-dominant hand
NMF	Non-negative matrix factorisation
PPB	Purdue Pegboard test
SD	Standard deviation

SE	Standard error
SW	Semmes-Weinstein test
TMS	Transcranial magnetic stimulation
UM	Unimanual
YA	Younger adults

Chapter 1 – Ageing & Manual Dexterity

1.1 Introduction

Between 2008 and 2018 the UK experienced a 22% increase in individuals aged 65 years old and over (~12.2 million in 2018) (Office for National Statistics UK, 2019). Similar trends are evident world-wide, with the US anticipating 88.5 million citizens aged 65 years old and over by the year 2050 (Seidler et al., 2010). With advanced age comes decline in motor function including reduced fine motor control, gait and balance, resulting in a reduced capacity to perform activities of daily living (ADL) (Seidler et al., 2010). For example, in the 65 – 69 age group 15% of individuals struggle with one or more ADL and require support, however, by the age of 85+ this figure rises to 1 in 3 people struggling to perform ADL and requiring care (Age UK, 2019). The consequence of reduced function in the elderly is two-fold – firstly, there is a humanist cost for individuals who struggle to care for themselves, and secondly, a growing economic burden for the subsequent care that is required to support these individuals. Older adults (OA) account for two thirds of recipients of social care, and around half the total spend on adult social care currently in the UK (Age UK, 2019). Current predictions estimate individuals aged 85 years old and over will almost double between 2017 to 2040 in the UK from 1.4 to 2.7 million (Office for National Statistics UK, 2019). Providing care for this volume of OA is not currently feasible based on current budgeting (Age UK, 2019). Consequently, we need to consider how we care for the elderly and what role science can play in helping older adults perform ADL and maintain their independence for longer.

1.2 Activities of daily living & reduced manual dexterity

Activities of daily living refer to the basic tasks of everyday life, such as eating, bathing, and dressing oneself (Wiener et al., 1990). When an individual is no longer able to carry out ADL they need help, which often comes from carers or mechanical devices (Age UK, 2019; Wiener et al., 1990). Many ADL require dextrous use of the upper limbs to reach, grasp and manipulate objects (Diermayr et al., 2011; Holt et al., 2013). Some tasks require the independent use of one hand such as drinking from a glass, whereas other tasks require a coordinated response from both hands; such as tying shoelaces or carrying a plate of food (Coats and Wann, 2012), being able to securely grip and manipulate objects is an integral part of many unimanual and bimanual ADL.

The specific ability to handle and manipulate objects is commonly referred to as ‘manual dexterity’ – defined as “the ability to use one’s hands’ or the ability to manipulate objects with the hands” (Desrosiers et al., 1995, pp 217). Manual dexterity can be further broken down into fine dexterity – referring to one’s ability to manipulate objects with the distal parts of the fingers, and gross dexterity – less refined movements of the hand and fingers. Daily tasks require both gross and fine aspects of dexterity – consider the control required to dress oneself, open/close drawers and manipulate objects for cooking and eating. Ageing leads to a decline in manual dexterity (Desrosiers et al., 1995). Once over the age of 60 years old manual dexterity shows a progressive decline, with OA displaying measurable drops in unimanual and bimanual manual dexterity over a three-year period (Desrosiers et al., 1999). Despite the strong evidence demonstrating OA reduced function during manual dexterity tests, such as the Purdue Pegboard (Desrosiers et al., 1995; Desrosiers et al., 1999) the precise mechanisms underpinning this decline are not well understood (Diermayr et al., 2011). The multitude of physiological changes that occur as a result of healthy ageing make pinpointing the precise mechanisms responsible for reduced manual dexterity a challenge. The following section provides a broad overview of the sensorimotor decline that occurs in the upper limb as a function of age. These findings are re-visited in chapter two where the sensorimotor control of grasping is covered in depth.

1.3 Sensorimotor decline and grasping

As we age there is a decrease in the number of motor units, muscle fibre size and the subsequent cross-sectional muscle area (Alnaqeeb and Goldspink, 1987; Hepple and Rice, 2016), leading to a reduced capacity to produce force. The reduction in muscle mass is accompanied by the central nervous system (CNS) becoming less efficient at transmitting signals to contract motor units (Delbono, 2003) – again resulting in a reduced ability to produce force. Interestingly, in OA, muscle mass loss in the forearm and hand occurs slower than in other areas of the body (Carmeli et al., 2003a). The muscles in the forearm and hand are central for securely gripping objects (Maier and Hepp-Reymond, 1995) and stabilising the wrist and digits when transporting and manipulating objects (Maier and Hepp-Reymond, 1995; Carmeli et al., 2003a; Holmes et al., 2015). The changes in muscle function result in OA having a reduced ability to produced peak grip forces during unimanual and bimanual tasks (Lin et al., 2014). However, within the OA population, peak grip force values are not well correlated with reduced manual dexterity (Murata et al., 2010), meaning other factors beyond maximum grip strength must be responsible for the reduced manual dexterity observed in OA (Desrosiers et al., 1995).

Successful grasping and lifting is also highly reliant on sensory input – vision provides critical information for locating objects during the reaching phase and for identifying contact points for the digits (Johansson and Flanagan, 2009b). Once the object has been grasped, cutaneous sensors innervating the glabrous skin regions play an important role in updating and refining grip force levels (Johansson and Westling, 1984; Johansson and Flanagan, 2009b). Evidence suggests younger and OA show similar eye movements during upper limb pointing tasks, but OA show a significant increase in the time taken to produce an initial eye movement and to begin transport of the hand towards the target (Warabi et al., 1986). OA also show a decline in the number of cutaneous sensors innervating the glabrous skin regions (Gescheider et al., 1994), which may reduce their ability to detect object shape through their digits (Johansson and Flanagan, 2009a) and make OA less responsive in detecting when an object is slipping from their grasp (Cole and Rotella, 2001).

Explaining the specific reasons why OA show reduced manual dexterity amongst the multitude of sensorimotor changes is a challenge (Diermayr et al., 2011). Questionnaires and functional tests can measure OA ability to perform ADL and grasping objects (Wiener et al., 1990; Platz et al., 2005), but these tests do not explain the mechanistic changes that cause worsening performance. It is also common for individuals to score well in functional tests and still complain of clumsiness when trying to grasp and manipulate objects (McDonnell et al., 2006). To find out more about OA reduced manual dexterity, researchers need to explore the kinematic and kinetic changes that occur when OA grasp and lift objects (Cole, 2009). The findings of such studies can help explain the mechanisms behind why OA struggle to grasp objects and in turn support OA in performing ADL.

1.4 Summary

The overall aim of this thesis is to better understand unimanual and bimanual grasping in OA and how it relates to reduced levels of manual dexterity. This chapter has highlighted the ageing problem we are facing in the modern world (Office for National Statistics UK, 2019), the subsequent humanistic and financial costs that are associated with caring for the elderly (Age UK, 2019) and the importance of grasping when performing ADL. Chapter two discusses the motor control of unimanual and bimanual grasping and the associated changes that occur as a result of age. Chapter two concludes by highlighting the current gaps within the literature surrounding grasping and OA. Chapter three evaluates the literature surrounding designing and testing tools to measure grasping, with a particular focus on building a tool to measure grasping in an older population. Chapter four (experiment 1) documents the building and testing of a tool designed during this thesis to measure the kinematics and kinetics of unimanual and bimanual grasping. Chapter five outlines general methods used in the subsequent testing of grasping in younger and older adult populations, before chapter six (experiment 2) establishes kinetic, kinematic and muscle coordination differences between younger adults and older adults present in unimanual and bimanual grasping strategies. Chapter seven (experiment 3) determines the differences in grasping strategies between OA with good and poor levels of manual dexterity. Chapter seven also establishes if OA with good manual dexterity show similar grasping strategies to younger adults, or emergent strategies as a result of healthy ageing. Chapter eight summarises the findings of the three experimental chapters, highlights future directions for research and discusses the implications of the thesis findings for helping OA perform grasping tasks and ADL.

Chapter 2 – Motor Control of Grasping & Lifting

2.1 Introduction

This chapter covers the motor control of grasping and how it relates to older adults (OA). Key terms are defined, before theories pertaining to grasping control are reviewed. The chapter then discusses the kinematics, kinetics, muscular control of grasping and what is known about grasping in OA. The chapter concludes by highlighting current gaps within the literature relating to grasping in OA.

The ability to reach (prehension) and manipulate objects are fundamental skills required to interact with our environment. Prehension involves two sub-goals – first, the hand must be transported to the object's location. Second, the hand must be scaled based on the size, shape and orientation of the object (Vollmer and Forssberg, 2009). Once these two goals have been achieved the object can gripped and lifted. The terms grasp and grip are often used interchangeably within the literature but strictly speaking, grip relates to the static hand posture once an object has been contacted, whereas grasping corresponds to the movement leading up to the grip (Wing and Lederman, 2009). In reality the process of grasping, gripping and lifting is not entirely linear – fingertip adjustments (Holt et al., 2013) and force adjustments (Johansson and Westling, 1984) are commonly observed after the object has been 'gripped' meaning hand posture is not entirely fixed once in place. However, for clarity, this thesis refers to grip as ones' ability to securely hold and transport objects using force applied through the fingertips (Wing and Lederman, 2009). Grasping will be used as a wider term to define both grip function and the movement of the hand either side of securely gripping an object.

There are two broad types of grip commonly referred to as the power grip and precision grip. The power grip involves an object being gripped in the palm on the hand, with all four digits and the thumb being wrapped around the object (Flanagan et al., 1996). Whereas, a precision grip is characterised as a lateral pinch between the thumb and index finger (Johansson & Westling 1984) and is used for fine motor tasks such as picking up a pen or unscrewing a bottle cap. Research in grasping and OA has predominantly focused on precision grip (Cole, 1991; Flanagan and Tresilian, 1994; Lowe, 2001) and variations of precision grip (Gorniak and Alberts, 2013) due to its important role in successfully performing activities of daily living

(ADL), such as eating, dressing and picking up small objects. Given this connection the focus of this thesis will be on the precision grip.

2.2 Measuring grasping

In 1984 Johansson and Westling pioneered a novel paradigm for measuring grasping using a grasp–hold–replace paradigm (Johansson and Westling, 1984). The task required participants to grasp and lift an object, holding it still in the air for 10 seconds, before replacing the object in its original position. The grasped object could measure the forces applied during the lift (figure 2.1) – these tools are known as manipulanda (plural) and are discussed in detail in chapter three. Since the 1980s, this methodology has been extensively used to measure healthy grasping and lifting (Gordon et al., 1991), age-related pathology such as stroke (McDonnell et al., 2006) and healthy ageing (Cole, 1991; Cole and Beck, 1994). The findings have advanced our understanding of motor control underpinning grasping in healthy adults (Johansson and Westling, 1984; Gordon et al., 1991; Nowak et al., 2001) and provided an understanding of specific grasping impairments in populations suffering from sensorimotor loss (Bleyenheuft and Thonnard, 2010; Diermayr et al., 2011). Three fundamental variables are measured during the grasp–lift–replace tasks to quantify the mechanisms of grasping: grip force, load force and the object's vertical position.

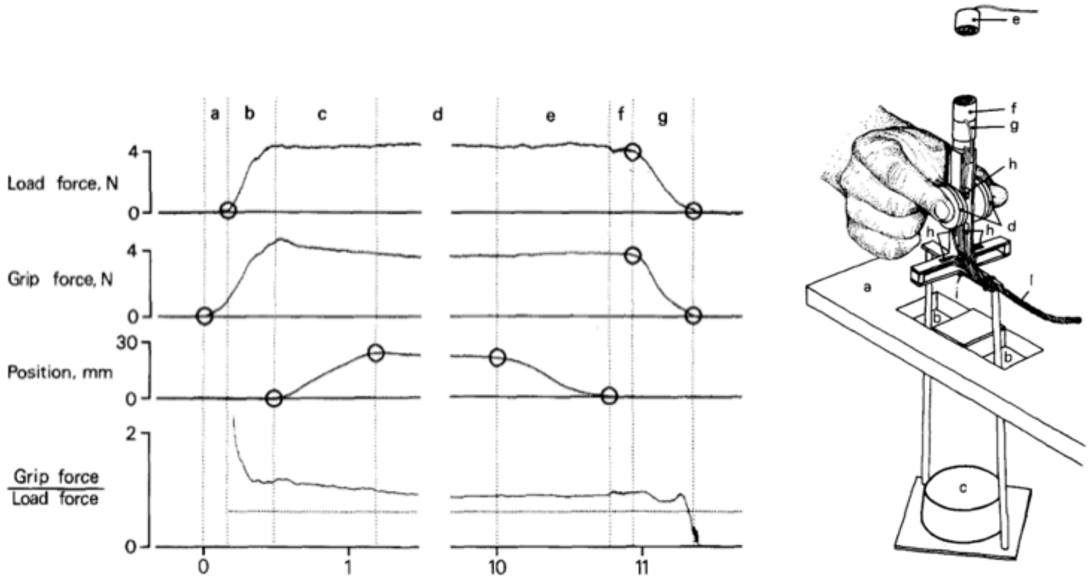


Figure 2.1: (Left) Example trial from the grasp–lift–replace task, with the load force, grip force, position data and grip force to load force ratio displayed. (Right) The manipulandum developed for the task. The manipulandum had two small discs joined to the manipulandum's body, with a hidden tray placed beneath the table allowing for additional mass to be added. Images adapted from Johansson and Westling (1984).

2.3 Grip force & load force

Grip Force (GF) is defined as the opposing forces created by the thumb and forefinger(s) when contacting an object (Zatsiorsky and Latash, 2009). The opposing digits apply equal and opposing GF vectors that result in the deformation of the pads of the thumb and finger tips and increase the contact surface area between the hand and object (Johansson and Westling, 1984; Zatsiorsky and Latash, 2009). The resulting friction creates a secure grip and ability to apply a vertical lifting force tangential to the grip surface known as the load force (LF) (Wing & Lederman, 2009). As LF increases above the objects' inertia, the object will begin to accelerate upwards and lift from its location. Once the object is airborne and stable the LF force remains equal to the weight of the object and acts in the opposing direction (Hermsdörfer et al., 2003). These two fundamental forces (GF and LF) require precise control for an individual to successfully grasp, lift and transport objects during activities of daily living (ADL). GF ensures enough friction is present to securely grip the object, whilst LF exerts itself in opposition to the weight of the object (figure 2.2) and regulates the acceleration of the object.

The relationship between GF and LF during grasping has been studied extensively (Johansson and Westling, 1984; Gordon et al., 1991; Flanagan and Wing, 1997; Parikh and Cole, 2012; Dimitriou and Buckingham, 2018). When lifting objects healthy individuals apply GF in advance and parallel to LF (figure 2.1). If GF falls too low relative to LF, the object will begin to slip – this ratio between GF and LF where the object begins to slip is known as the slip ratio (Johansson and Westling, 1984). Healthy individuals use a small level of GF above the slip ratio, to ensure a secure grip of the object, this additional GF used during grasping above the slip ratio is known as the safety margin (Augurelle et al., 2003). The key terms GF, LF, slip ratio and safety margin are used throughout this chapter when describing the motor control of grasping and lifting objects.

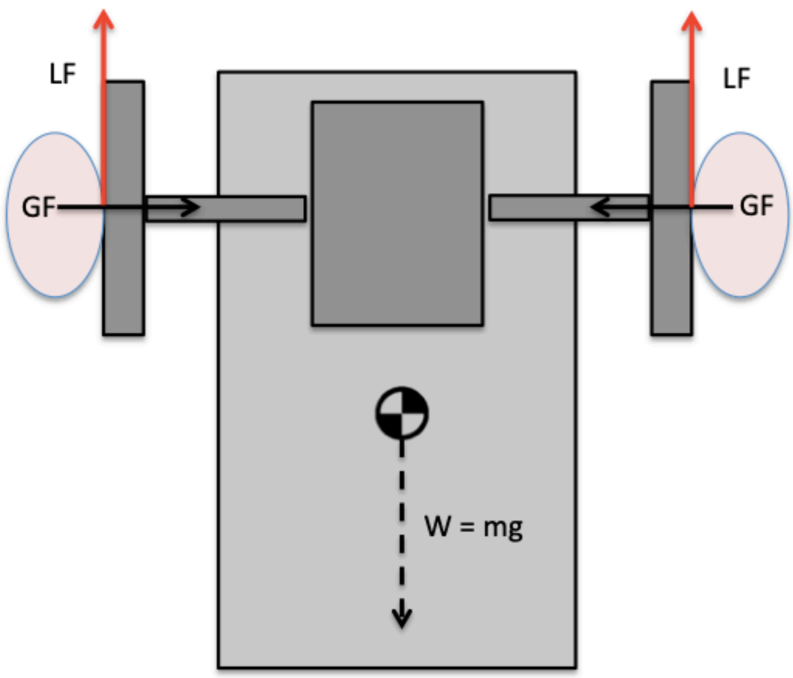


*Figure 2.2: A face-on view of digits grasping a manipulandum and the forces acting during the lift. Grip force (GF) – is applied by the thumb and opposing digit into the contact surfaces (solid black lines). The object's weight (W) = mass (m) * gravity (g) acts upon the objects centre of mass (dotted black line). Load force (LF) – is the upward lifting force, tangential to the grip surface (red lines) opposing to the object's weight.*

2.4 Theoretical models of force control during grasping

The simple task of grasping and lifting objects in the environment is underpinned by a complex interplay between sensorimotor systems, mechanical interactions and cognitive processes (Miall and Wolpert, 1996; Flanagan et al., 2001; Witney and Wolpert, 2007; Nowak et al., 2013). For example, grasping and lifting a mug of coffee begins with a decision to grasp the mug. This is followed by visually interpreting the mug's location, guiding the hand towards the mug and scaling the hand aperture appropriately to the object's width (Holt et al., 2013). Next, the object must be securely gripped – a prediction must be made about how much GF and LF is required for the up-coming lift – how heavy is the mug, how full is it with liquid, how slippery are the contact surfaces. Once the lift is underway, fast reactive adaptations are made to ensure the forces are suitable for performing the task (Nowak et al., 2013). Too little GF and the mug will slip, conversely sensing the mug as too heavy will lead to excessive LF and the mug being accelerated too quick, potentially spilling the coffee.

The scenario above highlights how object manipulation requires force scaling to first be predicted and then monitored and updated as the task is being performed (Nowak et al., 2013). This two-stage process was first alluded to during Johansson and Westling's seminal set of grasping and lifting experiments in the 1980's (Johansson and Westling, 1984; Westling and Johansson, 1984; Westling and Johansson, 1987). Since then, the exact workings of these anticipatory and reactive mechanisms have received great interest by researchers trying to understand force control during grasping. These two control phases are referred to using varying terminology within the literature including feed-forward and feedback control (Flanagan and Wing, 1997), predictive and reactive control (Witney et al., 2004) and anticipatory and reactive control (Nowak et al., 2001). For clarity this thesis will use the terms anticipatory and reactive control when referring to these systems of control.

2.4.1 Anticipatory control

Early studies within grasping (Johansson and Westling, 1984) showed that when objects are lifted GF is scaled in line and slightly ahead of LF (figure 2.1), providing strong evidence that the forces required to lift objects are initially predicted. These initial predictions are based on the object's visual properties (Gordon et al., 1991) with important signals including the object's size (Gordon et al., 1991) material (Buckingham et al., 2009) and form (Jenmalm and Johansson, 1997). Previous lifting experience with similar objects can also affect the anticipatory response seen during lifting (Witney and Wolpert, 2007; Kimpara et al., 2020). Suggesting there is a learned mechanism created by associating an object's physical properties such as weight, size and surface friction with the required anticipatory response. This anticipatory response is still present when an object about to be lifted is seen prior to the task, but is occluded during the grasp and lifting task (Buckingham and Goodale, 2010). In these situations, individuals still produce an anticipatory response suitable for the object they have just seen. Information gained when grasping and lifting an object with one hand can be easily transferred when lifting that object with the opposing hand – demonstrating the learned ability to scale force in an anticipatory fashion is also assessable across both hemispheres (Gordon et al., 1994).

The ability to anticipate the requirements of a task allows humans to initiate a motor response in situations where they have an incomplete picture of the task requirements. For example, instances where object properties such as mass and friction (Westling and Johansson, 1984) are unknown require force scaling to be initiated in an anticipatory manner, until the object has been lifted and afferent information can be used to update our estimations of object heaviness and slipperiness (Wolpert, 2007). This afferent response is not instantaneous: once sensory receptors detect force scaling is inadequate, time is needed for information to travel up afferent pathways, the signal to be processed, and a motor response to be relayed back to the muscles in the upper limb (Nowak et al., 2013). Initial research using grasp-lift-replace tasks showed participants begin updating GF ~0.1s into a lift when initial force scaling is not adequate, but these updates carried on much longer through the lift (Johansson and Westling, 1984) making the precise time windows used for updating forces difficult to measure. Subsequent research into this area explored the latency of the GF updates using two concurrent paradigms (Johansson and Westling, 1987). First, natural slips were induced, by creating an unexpected force, pulling the object down during a static hold task. Secondly, tactile sensors were artificially stimulated by electrically stimulating electrodes attached to the fingertips. In both cases a GF response was observed around 75ms after the stimuli (78 ± 10ms electric shock, 74 ± 9ms natural slip). Demonstrating a latency of around 75ms is required for updating GF from a permutation; and the important role haptic sensors play in updating GF (discussed in more detail in section 2.4.4).

2.4.2 Internal models

The initial anticipatory response used for force scaling and the ability to detect the need to update forces are considered products of an internal model used to control movement during grasping (Wolpert et al., 1998; Raghavan et al., 2006; Tanaka et al., 2019). Internal models are a stored representation of how to perform a grasping task and allow the programming of both grip and load force in anticipation of the expected sensory events arising from the lift (Nowak et al., 2013). An internal model framework suggests that when a grasping action is required two signals are created by the executive motor system (figure 2.3). A motor command is sent to the upper limb to initiate the grasp, alongside the motor command an efferent copy is created (Hermsdörfer et al., 2008). The efferent copy contains information about the sensory feedback that *should* arise from the action if performed correctly. This efferent copy creates a forward model that is used to predict the upcoming success of the grasping action (Bleyenheuft and Gordon, 2014). As actual sensory information returns via the afferent pathways (Johansson and Westling, 1987) a comparison is made between the predicted sensory outcome and the actual sensory information (figure 2.3). Any mismatch between the two signals is used to update the forward model, which in turn is used to update the force scaling as the grasping action continues (Nowak et al., 2013; Bleyenheuft and Gordon, 2014).

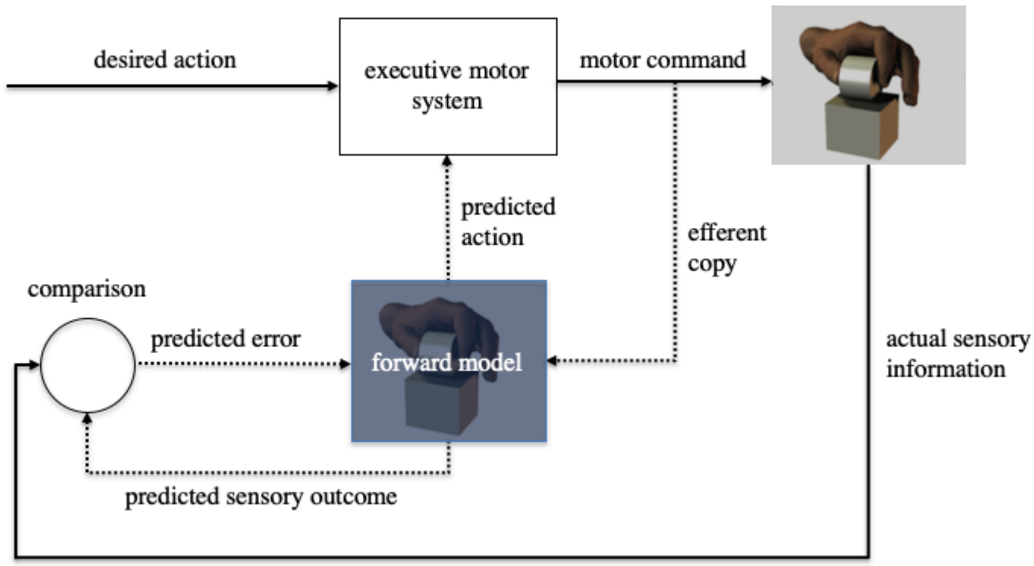


Figure 2.3: Internal model considered central for anticipatory and reactive force control during grasping. The desired action is fed into the motor system, which sends out a motor command to the upper limb and creates an efferent copy of the action – predicting the sensory response. The forward model anticipates the predicted sensory outcome and as actual sensory information is received a comparison is made between the predicted and actual sensory information. Any error is fed into the forward model and used to update the motor command. Image adapted from (Nowak et al., 2013).

2.4.3 Reactive control

The updated force scaling based on sensory feedback is known as reactive control (Nowak and Hermsdörfer, 2006). Such reactive responses may be visible with latencies as short at ~75ms (Johansson and Westling, 1987), but previous research has shown such reactive responses are on-going throughout the lift (Westling and Johansson, 1984). Consequently, the process outlined in figure 2.3 is a continuous cycle that occurs throughout the grasp and lift (Kimpara et al., 2020). Predictions are continuously being made by the forward model and comparisons made to afferent information as it becomes available. Updates in force scaling may not be necessary if initial predictions of the required GF and LF are accurate, however when initial task predictions are inaccurate, or unexpected permutations occur within a task, a reactive response is required. Reactive force control was first studied by Johansson and Westling (1984) who altered the mass of objects between trials. In their study mass was added and subtracted via a tray under the table that was occluded from participants. When the mass changed between trials both GF and LF were programmed based on the mechanical properties of the previous lift – resulting in incorrect levels of GF and LF being applied to the objects (Johansson and Westling, 1984; Nowak et al., 2013). This initial error within the motor command was detected and subsequently updated during the lift (figure 2.4).

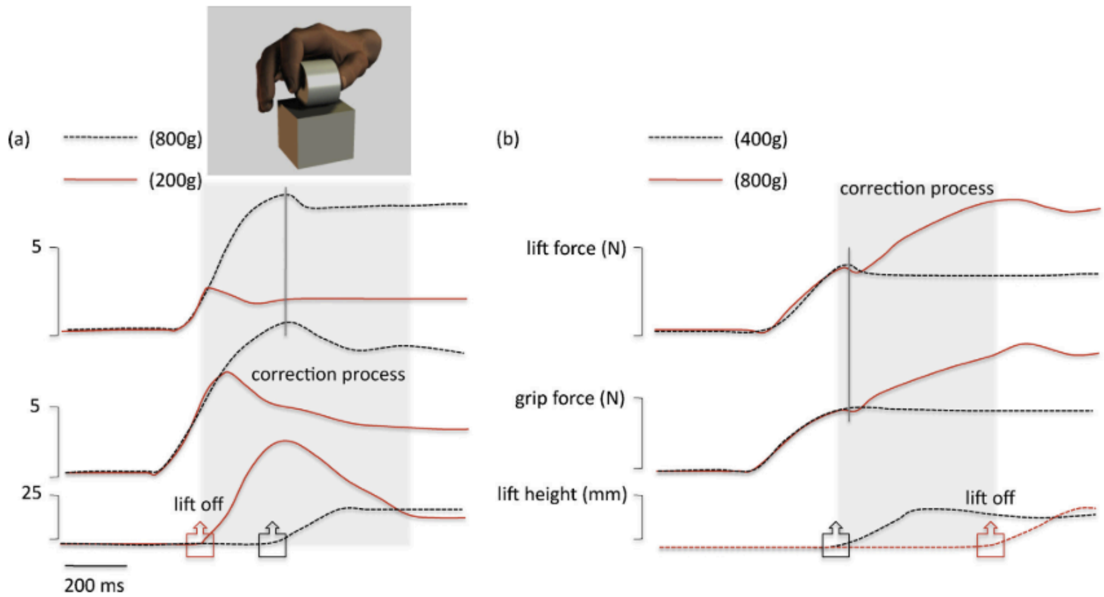


Figure 2.4: Traces of lift (load) force (top), grip force (middle) and object position (bottom) for a right-hand lift of (a) a known 800g object followed by a lift of a 200g object (of identical visual appearance) and (b) a known 400g object followed by a novel lift of a novel 800g object (identical visual appearance). The erroneous force planning when lifting the novel objects of unexpectedly lighter (a) or heavier (b) weight trigger a reactive response. Figure adapted from Nowak et al. (2013).

Jenmalm and colleagues investigated the underlying neural correlates associated with these reactive updates using functional magnetic resonance imaging (fMRI) (Jenmalm et al., 2006). Their study involved repeatedly lifting an object of either light (230g) or heavy (830g) mass with their right-hand before the object was unexpectedly changed to the opposing mass condition (heavy -> light or light -> heavy). Again, this was achieved by adding and subtracting mass to a tray that was occluded from the participant. They found that, regardless of whether the weight was heavier or lighter than predicted, activity was found in the right inferior parietal cortex (supramarginal gyrus), suggesting this region is involved in comparing the actual sensory response to the predicted response. When the weight was heavier than predicted the reactive increase in GF was correlated with activity in the left primary motor and somatosensory cortices. However, when the weight was lighter than predicted there was a fast termination of excessive force which was associated activation within the right cerebellum (Jenmalm et al., 2006). These findings suggest that the reactive control of grasping is spread across many cortical regions, and that differing areas may be activated depending of if reactive responses require an upregulation or downregulation in forces (Jenmalm et al., 2006; Nowak et al., 2013).

2.4.4 Integration of sensory information

The reactive updates observed during grasping are a function of: i) predicting sensory responses and ii) comparing predictions to actual sensory information (figure 2.3) (Bleyenheuft and Gordon, 2014). For reactive control to be successful, the motor system must continuously attune to relevant sensory information during grasping and object manipulation (Nowak et al., 2013). Dextrous manipulation of an object can be broken down into action phases, with behavioural events signalling the successful completion of a given sub-goal (Johansson and Flanagan, 2009b). For example, contact between the digits and the object marks the end of the reach phase and the beginning of the loading phase, the separation between the object and table denotes the end of the loading phase and the beginning of the transport phase (Johansson and Westling, 1984). Many of these events provide feedback from more than one sensory channel. Consider an object being placed back onto a table – this event will lead to a decrease in load forces detected by mechanoreceptors innervating the digits in contact with the object (Westling and Johansson, 1987), but will also lead to an auditory signal as the object contacts the table and the event can be detected visually if the object and surface are in view (Johansson and Flanagan, 2009b). Understanding how the motor system uses inputs from our senses at each of these stages provides a deeper understanding of the sensorimotor nature of grasping. It also provides a better framework for understanding why OA may struggle when performing grasping actions (Cole, 2009).

Three studies provided great insight into the role mechanoreceptors play during: i) grasping (Westling and Johansson, 1987) and ii) their role in updating GF during slips (Johansson and

Westling, 1987; Macefield et al., 1996). All three studies recorded impulses from tactile afferents innervating the glabrous skin. These recordings were made using tungsten electrodes placed within the median nerve. The responses captured by the electrode were categorised into slow-adapting type one and two (SA-1, SA-2) and fast adapting type one and two mechanoreceptors (FA-1, FA-2) based on prior data collection whilst stimulating the digits using a force probe stimulator. Please see Johansson and Westling (1987) for the full methodology defining this process and Johansson and Flanagan (2009a) for a wider discussion surrounding the coding of afferent signals. The results of these three studies (Johansson and Westling, 1987; Westling and Johansson, 1987; Macefield et al., 1996) form a fundamental part of the discussion below.

Grasp contact

Upon contact with the object our fingertips rapidly deform, increasing the contact area between the digits and object (Zatsiorsky and Latash, 2009). During this initial contact and object release FA-1 and SA-1 sensors both show increased firing, based on median nerve recordings (Westling and Johansson, 1987) highlighting the central role these sensors play in detecting initial contact and object release. The information relayed by each digit builds a rich picture of the respective contact between hand and object, with the firing rate of FA-1 and SA-1 receptors reflecting the force intensity between the digits and object – increased firing rates detected in median nerve recordings were associated with increased grip forces (Westling and Johansson, 1987). The activation of FA-1 and SA-1 receptors signal that the object has been gripped – leading to the initiation of the loading phase. SA-1 receptors continue to fire during the loading phase, within SA-2 receptors showing increased firing rates relating to the increasing load force causing the skin to stretch (Westling and Johansson, 1987). The transition from contact to loading is delayed when weak, single-pulse transcranial magnetic stimulation (TMS) creates a disturbance within the contralateral primary sensorimotor cortex just prior to contact (Lemon et al., 1995). Potentially indicating its role in processing incoming afferent information and/or sensory predictions. Similar findings have been found when applying TMS to the anterior intraparietal area (AIP), located within the posterior parietal cortex during grasp-lift-replace tasks (Davare et al., 2007). Davare and colleagues found that using TMS to create a virtual lesion in the left AIP 170 - 120ms before contact was enough to affect grip force scaling in either hand (Davare et al., 2007). Again, indicating the AIP might play a role in processing incoming afferent information and/or sensory prediction during initial stages of grasping.

Grasp stability & object transport

Once the object is securely grasped GF and LF increase in parallel as the individual prepares to lift the object (Johansson and Westling, 1984; Nowak and Hermsdörfer, 2006). FA-1 receptors show a reduction in firing rate after initial contact, whilst SA-1 and SA-2 receptors continue to generate signals providing feedback that the object is being gripped by each digit (Westling and Johansson, 1987). As the object is lifted from the surface, FA-2 receptors show a burst of activity (Westling and Johansson, 1987), suggesting these receptors provide feedback on when the lift phase is underway and terminated (figure 2.5). This timepoint also marks the first instance where true weight of the object is known, which implies the firing of FA-2 receptors as the object is lifted mark an important moment where the anticipatory GF and LF can be compared to the true mass and frictional components of the object (Johansson and Flanagan, 2009a; Flanagan et al., 2009). Occasionally, during object transport, the forces applied are not sufficient to hold the object securely. In these instances the object will begin to slip (Johansson and Westling, 1984). Such a slip usually results in the unloading at one digit, which consequently increases the loading on the remaining digits (Johansson and Flanagan, 2009b). The momentary changes in LF are detected by FA-1 afferents, which initiate a reactive response, increasing levels of grip force 75 - 90ms after the initial slip (Johansson and Westling, 1987; Macefield et al., 1996). Interestingly, the firing of FA-1 afferents is reduced under higher levels of static finger force, but FA-1s do not directly respond to these static finger forces (Macefield et al., 1996), suggesting FA-1 firing is only present when GF levels are low and a there is limited pressure between the fingertips and object.

Vision provides important information pre-grasp about the location of the object, its size, form and potential weight (Gordon et al., 1991; Jenmalm and Johansson, 1997; Buckingham et al., 2009). During the grasp phase vision cannot provide direct information about the mechanical forces at play between the object and the hand, unless the object is dropped (Johansson and Flanagan, 2009b). Consequently, mechanoreceptors innervating the glabrous skin regions are considered the central mechanism used for force scaling during secure grasp and transport phases (Westling and Johansson, 1987; Johansson and Flanagan, 2009a). Analysis of eye movements suggest vision is used to support the planning and control of up-coming grasping movements (Johansson and Flanagan, 2009a). An eye-tracking study where participants were instructed to grasp a small bar and lift it upwards to press a target switch found participants fixated on important landmarks for the up-coming stage of the task (Johansson et al., 2001). During the reach phase, gaze was fixed on the section of the bar that was about to be grasped. As the object was gripped, gaze was updated to fix on the target switch for the up-coming transport phase. Subjects never fixated on the hand or the moving bar (Johansson et al., 2001). Spatial information about the object's location and target location cannot be determined through haptic systems. Therefore successfully grasping and transporting objects requires the integration and parallel processing of vision to provide spatiotemporal information about the hand and object (Johansson et al., 2001; Johansson and Flanagan, 2009b; Cashaback et al., 2017) while the mechanoreceptors in glabrous skin regions regulate force scaling (Westling and Johansson, 1987; Johansson and Flanagan, 2009a).

Two separate reviews of literature (Johansson and Flanagan, 2009a; Johansson and Flanagan, 2009b) have considered how sensory information is used to regulate the grasp-lift-replace task. The synthesis of their findings is presented below in figure 2.5. The top of the figure (a) outlines the sub-goals for the task and example LF, GF and position data. It also highlights the anticipatory predictions made for the up-coming sub-goals (Johansson and Flanagan, 2009a). The bottom section (b) of figure 2.5 highlights the integration of tactile signalling during the grasp-lift-replace task (Westling and Johansson, 1987). The middle section of figure 2.5 highlights where the predicated sensory outcomes for the task are compared to the actual sensory information, for each stage of the task (Nowak et al., 2013). Figure 2.5 does not explicitly display the contribution of vision. However, based on previous research visual information would be an integral source of feedback: i) as the object is transported up to its target height, and ii) during the replace stage as the object is lowered back onto the table (Johansson et al., 2001).

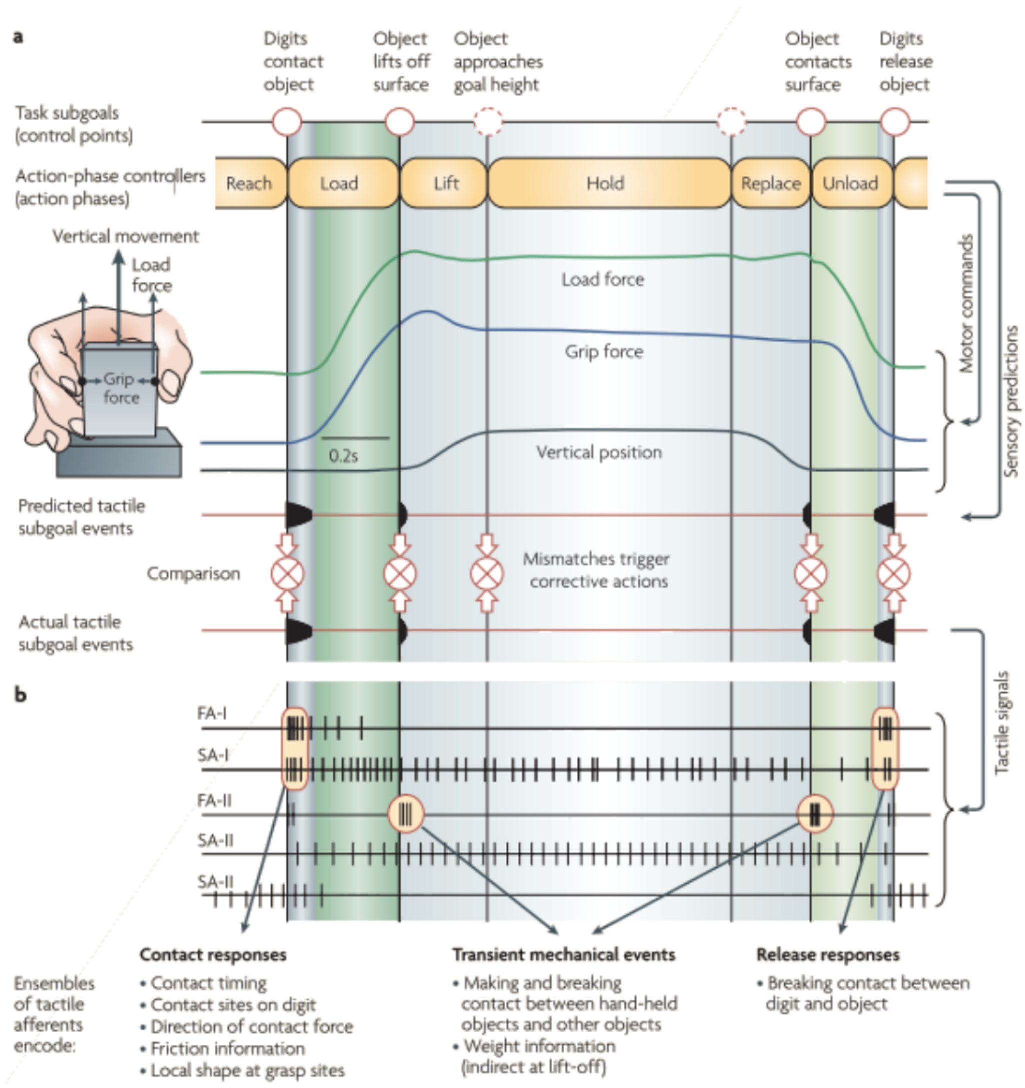


Figure 2.5: Part a: The key phases of grasping and lifting with the associated sub-goals. Grip force and load force are shown for each phase and represent the motor commands sent to the upper limb. Beneath the motor commands are a timeline of the anticipated sensory response. Part b: Tactile afferent signals and their firing during sub-goals. The area between a and b represents the comparison between anticipated and actual sensory information, with corrective actions taken when there is a mismatch in information. The figure is adapted from (Johansson and Flanagan, 2009a). Vision is not explicitly stated on the diagram but is considered part of the predicted and actual sensory events, with a high emphasis placed upon vision during lift and replace phases.

2.5 Bimanual grasping

To this point, grasping has been discussed in a unimanual context. However, many ADL require the coordinated effort of both hands simultaneously to pick up, manipulate and transport objects – known as bimanual grasping (Vieluf et al., 2015). Bimanual actions can require both hands to work together to pick up one large object (Bracewell et al., 2003), such as carrying a tray of food, or can require the two hands to perform differing actions, but remain temporally and spatially orchestrated, such as cutting up food with a knife and fork (Endo et al., 2009). Previous grasping research has shown that healthy individuals are able to scale grip forces independently for each hand, regardless of the two hands holding similar (both 400g) or differing (400g and 200g) levels of mass (Dimitriou and Buckingham, 2018). When lifting events become temporally uncoupled (one object is held stationary in the air, whilst the other hand begins a lift) both hands are still able to scale grip force appropriately and independently to lift and hold objects (Dimitriou and Buckingham, 2018). These findings suggest that during bimanual grasping the forces used by each hand can be scaled independently, with the actions of one hand showing little influence over the other.

Bimanual grasping still shows anticipatory and reactive characteristics similar to unimanual grasping (Bracewell et al., 2003; Diedrichsen et al., 2005; Witney and Wolpert, 2007). Diedrichsen et al. (2005) assessed bimanual anticipatory control by asking participants to hold a weighted object with one hand under a table (palm up – called the postural hand), before removing the object with their other hand. During this condition the postural hand remained stable during object removal, suggesting participants could predict the up-coming change in load force being applied by the lifting hand and update the postural hand accordingly. In a second condition an external source removed the object which resulted in a sharp, upward acceleration of the postural hand – indicating no anticipatory response (Diedrichsen et al., 2005). Similar findings are presented by Witney and Wolpert (2007), in their experiment individuals gripped handles with both hands. In the first condition participants pulled the left-hand lever, which induced a load force onto the right hand. In the second condition a load force was applied to the right hand with no prior warning. Again, participants showed anticipatory GF responses in condition one, when the load could be anticipated, but not in condition two (Witney and Wolpert, 2007). These findings suggest that actions performed with one hand are fed into the forward model and used for planning anticipatory responses with the other hand when necessary (Witney and Wolpert, 2007). Within the study cited above Diedrichsen and colleagues (2005) included two participants lacking a corpus callosum and individuals with unilateral and bilateral cerebellar damage. Both acallosal participants maintained the ability to anticipate the unloading of the object with their lifting hand and stabilise their postural hand, whereas individuals with unilateral and bilateral cerebellar damage showed impaired anticipatory responses – they were less able to stabilise the postural hand. These findings indicate that anticipatory control during bimanual tasks is regulated at a sub-cortical level (without the need for the corpus callosum sharing information between hemispheres) and suggests the cerebellum plays an integral role in regulating anticipatory control between hands during bimanual tasks (Diedrichsen et al., 2005).

Reactive bimanual control has been explored by Bracewell and colleagues (2003) – participants held a tray stable in the air, using both hands with their eyes closed. In three separate conditions weights (200g or 400g) were dropped onto i) the centre of the tray or closer to ii) the dominant or iii) non-dominant hand. The results found that both hands showed a reactive GF response around 75ms after the increase in LF, indicating similar reactive latencies to those seen during unimanual grasping (Johansson and Westling, 1987; Macefield et al., 1996). Interestingly, both hands showed tight GF coupling in their reactive response, irrespective of where the weight was dropped onto the tray, suggesting reactive bimanual control of GF may show greater synchronisation between hands (Bracewell et al., 2003) than GF scaling during anticipatory phases of grasping (Dimitriou and Buckingham, 2018).

2.6 Grasping in older adults

The most commonly reported grasping change observed in OA is elevated GF profiles during initial stages of the lift and during the hold phase (Cole, 1991; Cole and Beck, 1994; Gilles and Wing, 2003; Danion et al., 2007). Despite the volume of data surrounding this finding, the cause for the elevated GF profiles are still a matter of debate (Diermayr et al., 2011). Early research within this area cited OA exhibiting higher slip ratios compared to younger adults (YA) (Cole, 1991; Kinoshita, 1996), due to OA having slipperier skin. The slipperier skin results in a lower coefficient of friction, thus more GF is required to securely grip objects (Cole, 2009). Nonetheless, the rise in GF recorded in most studies is greater than the associated changes in skin slipperiness, meaning OA create a greater safety margin during grasping compared to YA (Kinoshita, 1996; Cole et al., 1999; Cole and Rotella, 2001). This increased GF and associated safety margin have been attributed to the age-related deterioration in fingertip sensitivity (Cole, 1991; Kinoshita, 1996) with a larger safety margin resulting in a reduced need to make fast, reactive force adjustments if an object begins to slip (Diermayr et al., 2011) – such updates are regulated by FA-1 mechanoreceptors (Johansson and Westling, 1987; Macefield et al., 1996), which are known to be depleted in OA (Gescheider et al., 1994).

Research surrounding anticipatory grasping control in OA has led to mixed findings. Cole et al. (1991, 1999) performed unimanual grasp-lift-replace studies with YA and OA. In both studies OA participants scaled GF before LF during the initial stages of the lift, with GF and LF showing similar rates of force development, suggesting anticipatory control in OA is mostly unaffected (Cole, 1991; Cole et al., 1999). Results from Cole (1991) found OA show similar anticipatory control to YA and can adapt anticipatory forces appropriately for objects with varying frictional properties. However, in all frictional conditions OA did show increased levels of GF and safety margins compared to YA. Cole et al. (1999) progressed these findings to demonstrate that during experiments where object friction randomly varies, OA scale initial forces in preparation for the most slippery surface regardless of the condition. Whereas YA create anticipatory forces more appropriate for the frictional surface in place. These changes between YA and OA were considered a learned strategy used by OA to reduce the chance of dropping an object, rather than a reduced ability to scale forces in an anticipatory manner (Cole et al., 1999). OA also show similar abilities to YA in updating anticipatory GF, based on previous lifts (Nowak et al., 2013). Cole and Rotella (2002) carried out a grasp-lift-replace study where visually identical objects that varied in mass and friction were lifted in a random order. Both YA and OA showed anticipatory GF responses suited to the previous object lifted (Cole and Rotella, 2002), indicating anticipatory responses were continually updated in both YA and OA. From this body of literature, OA appear to show little change in anticipatory control, maintaining the ability to scale GF in advance of LF (Cole, 1991), adapting responses to varying grasping surfaces (Cole, 1991; Cole et al., 1999) and updating anticipatory responses, based on previous lifts (Cole and Rotella, 2002).

However, studies exploring anticipatory force control during dynamic cyclical movements show less clear-cut results. In Gilles and Wing's (2003) study, YA and OA performed vertical oscillating movements whilst GF and LF were measured. While the time to peak GF and LF were less well correlated in the OA group indicating anticipatory force scaling might be inhibited, this finding was not statistically significant. Danion and colleagues (2007) performed a similar study but oscillating in a horizontal plane. A cross-correlation was performed between GF and LF, YA showed adjustments in GF occurring in advance of LF (+7ms) whereas OA showed a delayed response in GF updates (-26ms). Also the relationship between GF and LF (correlation coefficient) was lower in OA compared to YA, suggesting GF was scaled less accurately to the anticipated levels of LF (Danion et al., 2007). The lower cross-correlation coefficient between GF and LF and time-shift seen in OA indicate anticipatory control is less effective compared to YA.

OA still exhibit reactive responses during grasping; similar to YA. Cole and Rotella (2001) asked participants to grip a rigid, steel handle and minimise any movement as an attached motor applied a loading force. Both YA and OA groups reacted to the unexpected load forces with an increased GF visible ~80ms after the load force stimuli, the increase GF response was greater in OA compared YA (Cole and Rotella, 2001). Nonetheless, these findings indicating similar cutaneous, reactive mechanisms are present and working in OA to that seen in YA (Johansson and Westling, 1987). However, when load forces were applied gradually (2N/s) there was a delayed response in the OA of 110ms compared to YA (Cole and Rotella, 2001). Indicating that OA are less able to trigger a reactive responses to slow adapting, small force stimuli, potentially due to their reduced tactile sensitivity (Gescheider et al., 1994). The findings presented in this section highlight that OA still show anticipatory and reactive capabilities during grasping, but small differences are present in the accuracy and timing of anticipatory responses (Danion et al., 2007) and their ability to produce reactive GF updates (Cole and Rotella, 2001).

2.6.1 Bimanual grasping in older adults

Bimanual age-related studies in grasp-lift-replace paradigms have received limited attention to date (Cole, 2009). Consequently, there is limited data surrounding anticipatory and reactive bimanual grasping in OA. However, adjacent paradigms do provide some insight into bimanual grasping control in OA. Gorniak and Alberts (2013) asked YA and OA to connect and disconnect two independent objects that slotted into one another. One hand was used to grip each object with the GF and LF being measured throughout the task. The findings showed that OA used elevated GF profiles throughout the task (Gorniak and Alberts, 2013), suggesting similar grasping strategies to those used in unimanual tasks (Cole, 1991). These elevated levels of GF also led to an increased safety margin observed in OA, apparent in both static and dynamic phases of the task (Gorniak and Alberts, 2013). There is also evidence that OA take longer to appropriately scale forces during bimanual paradigms. Lin and colleagues (2014) asked YA and OA to grip fixed dynamometers with both hands and scale GF to 10, 20 and 40% of maximum voluntary levels (calculated beforehand). OA took significantly longer to scale GF to the target level of 20% compared to YA. The longer time required to scale force to desired levels may impact OA ability to successful perform bimanual grasping tasks (Lin et al., 2014). Studies assessing bimanual force control in healthy OA and age-matched stroke patients have shown that healthy OA are still able to coordinate wrist (Kang and Cauraugh, 2014) and finger forces (Lodha et al., 2012) between hands to match sub-maximal target forces (5 - 50% max force). The healthy OA group applied equal levels of forces with their dominant and non-dominant hands to reach the target force, whereas age-matched stroke patients showed far greater asymmetry in force contributions between hands (Lodha et al., 2012; Kang and Cauraugh, 2014).

These findings indicate that, similar to unimanual tasks, OA still use elevated levels of GF during bimanual tasks compared to YA, to ensure they have a high safety margin when holding and transporting objects (Gorniak and Alberts, 2013). OA appear capable of coordinating force responses during bimanual tasks, with the ability to apply symmetrical forces with both hands when required (Lodha et al., 2012; Kang and Cauraugh, 2014). However, OA take longer to reach appropriate force levels during bimanual tasks compared to YA (Lin et al., 2014). Such findings are useful but provide limited insight into the anticipatory and reactive bimanual grasping strategies present in OA during functional grasping and lifting tasks. More research is required to better understand bimanual anticipatory and reactive grasping adaptions that occur as a result of ageing.

2.7 Muscle control of grasping & lifting actions

Task level goals, such as reaching for an object or drinking from a cup, need to be translated into a complex set of muscle activation patterns in order to perform the movement (Ting and McKay, 2007). The architecture of the human hand is highly specialised for the task of grasping and dextrously manipulating objects – 39 muscles located in the forearm (extrinsic muscles) and the hand itself (intrinsic muscles) shape the digits during grasping (Brochier et al., 2009) and apply forces to objects during gripping tasks (Maier and Hepp-Reymond, 1995; Hoozemans and Van Dieën, 2005). Each of these muscles are made up of underlying motor units, capable of individually firing to adapt and refine movements during grasping and object manipulation (Huesler et al., 2000; Hug and Tucker, 2017). Understanding how the central nervous system (CNS) selects and controls muscle activity during grasping to produce such fine control is challenging, but a central question in understanding the decline of grasping in OA (Cole, 2009).

The grasping and transport of objects requires muscle forces to accurately carry the limb to the object (Calabro and Perez, 2016), successfully grasp the object and securely grip the object during transport (Maier and Hepp-Reymond, 1995). The reaching phase requires activation of muscles in the upper arm, with the anterior deltoid playing a central role when flexing the shoulder toward the object and elevating the arm and object post grasp (Lemon et al., 1995). The intrinsic hand muscles, located in the thumb (abductors and flexors) and index finger (intrinsic and long flexors), are prime movers when creating a precision grip and applying subsequent grip force during precision grip tasks (Maier and Hepp-Reymond, 1995; Johanson et al., 2001). As the digits narrow their aperture and ready for grip, the muscles in the hand show increased levels of coactivation ~65ms before contact to stiffen the digits before applying an isometric force into the surface (Venkadesan and Valero-Cuevas, 2008). Coinciding with the onset of grip force, forearm flexor and extensor muscles co-contract to assist with force production but also to stabilise the wrist joint during the grasp and lift (Maier and Hepp-Reymond, 1995; Holmes et al., 2015).

Specific muscle coordination patterns are also present in the hand during grasping to regulate the levels and direction of grip forces. Cross-correlation analysis between grip force production and EMG amplitude show that both thumb flexors (abductor pollicis brevis, flexor pollicis brevis and flexor pollicis longus) and extensor muscles (and extensor pollicis longus) amplitudes increase with force production. The increased activation in both thumb flexors and extensors reflects the need to stabilise the thumb joint during grasping and transporting objects (Maier and Hepp-Reymond, 1995; Johanson et al., 2001). Instances where additional load force is applied to a gripped object results in increased finger and thumb muscle activation creating a reactive response in GF, with the abductor pollicis brevis showing a notable increased activity at this timepoint (Cole and Abbs, 1988). The evidence above outlines specific roles muscles play during the grasping and lifting of objects. However, successful grasping and lifting requires a coordinated response of all joints in the upper arm and precise grip force regulation throughout the task. Understanding how muscle activity is coordinated to achieve the observed behaviour of successful grasping is a complex matter, but central in understanding age-related decline in grasping.

2.7.1 Muscle synergies in grasping

As electromyography (EMG) research in grasping has progressed there has been a growing trend towards exploring how individual muscles are coordinated to successfully grasp objects. Evidence suggests hand actions are controlled at the level of synergies, not single muscles (Prevete et al., 2018). Muscle synergies comprise of coordinated activations of groups of muscles, with time-varying profiles (D'Avella et al., 2006). From this perspective, control of movement is simplified as the central nervous system (CNS) has to control far fewer parameters across the movement cycle. Such an approach makes sense when considering the large number of individual muscles that require control during a grasp – for example, even making small adjustments to fingertip forces has been shown to require coordinated response from multiple muscles within the forearm, hand and thumb (Poston et al., 2010; Santos et al., 2010; Wu et al., 2018).

Kinematic analysis of hand posture when grasping various objects (n = 51, including an apple, banana, brick and calculator) and subsequent analysis of joint angles in the fingers and thumb used during the grasping tasks have shown only a few variations of joint angles are used to grasp a wide-ranging array of objects (Santello et al., 1998), indicating a select few muscle activation patterns may be responsible for controlling grasping of many different objects. D'Avella and colleagues (2006) explored upper-limb muscle synergies during fast reaching movements using non-negative matrix factorisation (NMF). NMF is a data reduction technique that aims to find underlying patterns that best represent complex dataset – in this instance groups of muscles that may be working as a single synergy, based on similar amplitude profiles throughout a task. D'Avella and colleagues found that a small number (4 or 5) of muscle synergies could explain (73–82% data variation explained) the organization of 19 muscles located in the shoulder and upper arm during fast-reaching movements in different directions.

The small number of muscle synergies were able to consistently explain the activation of 19 muscle during: i) varying pointing tasks, ii) pointing with pronated and supinated hand positions and iii) pointing whilst holding objects of varying mass (D'Avella et al., 2006). The results suggest the large groups of muscles needed to control upper-limb tasks may be control in a synergistic manner – with multiple muscles grouped and regulated together to simplify the control of movement (Delis et al., 2014). Such findings suggest the CNS might perform grasping and lifting tasks in a similar way, where muscles are controlled in synergistic groups, rather than individually activated, making grasping and lifting tasks easier to control. Subsequent studies have applied NMF to explore muscle activation patterns in a other upper and lower limb tasks including: reaching and pointing tasks (Delis et al., 2014) and cycling (Hug et al., 2010). Delis and colleagues (2014) found that NMF analysis during pointing tasks could differentiate muscle coordination patterns used for pointing in different directions and that the reconstruction of EMG data from the NMF output was consistently high across different participants (n = 5) (Delis et al., 2014). Which indicates NMF's ability i) to explain muscle coordination patterns used across different variations of a task and ii) to account for individual variance in muscle coordination between participants.

NMF analysis decomposes multiple muscle signals into smaller groups of functional muscle synergies, best representing the original data (D'Avella et al., 2006). These outputs have two components. i) Muscle weights – fixed factors that represent the muscle's weighting within a given synergy. ii) Temporal profiles – a waveform that represents each synergy's contribution to the overall muscle activation across time (Hug, 2011). NMF provides a useful approach for exploring muscle control during movement, the simple and easy in interpret outputs are a key benefit of NMF, when compared to more abstract decomposition algorithms; such as principle component analysis (Ebied et al., 2018). Nonetheless, NMF relies heavily on the hypothesis that the CNS uses a fixed sets of muscle synergies to perform a given task that are subsequently reused across trials. From this perspective muscle synergies are seen as 'invariant' across trials (Delis et al., 2014). In contrast the temporal coefficients – the neural drive that recruits the synergies are 'sample-dependent' and vary from trial to trial (Delis et al., 2014).

The summation of muscle synergies and their temporal coefficients have consistently been shown to provide strong estimations of original muscle activity across motor tasks and a useful interpretation of how the CNS controls muscles for a given task (D'Avella et al., 2006; Hug et al., 2010; Delis et al., 2013). To date, NMF analysis has not been applied to explore muscle synergies during grasp-lift-replace tasks. However, such an approach does offer a promising methods to better understand how muscles in the upper limb and hand are organised during successful grasping (Maier and Hepp-Reymond, 1995; D'Avella et al., 2006; Holmes et al., 2015).

2.7.2 EMG analysis in older adults grasping

Ageing results in a loss of muscle fibres and atrophy of the muscle fibre structure, resulting in a reduced capacity to generate force (Marmon et al., 2011; Hepple and Rice, 2016). Research has also documented changes in the way muscles function between YA and OA during daily tasks such as walking (Kang and Dingwell, 2009), stabilising posture (Benjuya et al., 2004) and when gripping objects (Keenan et al., 2012). Upper-limb ageing studies to date have evaluated muscle-muscle coherence in the frequency domain (Keenan et al., 2012) and assessed EMG signal complexity using entropy analysis (Wu et al., 2018), but have provided limited analysis of EMG data in the time domain. Analysis within the time-domain may provide a useful insight into where within specific grasping tasks OA start to show changes in their muscle activation patterns.

Previous EMG studies in the time domain have shown OA display increased peak muscle amplitudes in lower limb muscles during walking compared to YA (Kang and Dingwell, 2009). OA also exhibit increased coactivation of antagonist muscles during lower-limb force production tasks (Macaluso et al., 2002). Peak EMG amplitudes are also more varied from trial-to-trial in OA during walking tasks compared to YA (Kang and Dingwell, 2009). Findings such as increased coactivation and EMG amplitudes provide a deeper insight into the muscular coordination patterns that underlies the behavioural changes observed in OA (Kang and Dingwell, 2009). A similar approach of exploring temporal EMG patterns throughout the grasp-lift-replace task may help explain the grasping kinetics observed in OA (Cole, 1991; Danion et al., 2007; Diermayr et al., 2011). Applying NMF analysis to the data collected may also help explain changes in how muscles are coordinated between YA and OA.

Additionally, EMG analysis during grasping may provide deeper insight into the anticipatory responses observed in YA and OA. Kaneker and Aruin (2014) applied EMG analysis to study anticipatory postural control in YA and OA. Their study involved a swinging pendulum being caught by participants who were asked to maintain a balanced posture. Both YA and OA created an observable anticipatory response to alter their centre of mass and pressure when the pendulum was approaching, but EMG data in the trunk and lower-limbs revealed that OA created a delayed onset of muscle anticipatory responses, followed by a greater magnitude of muscle activation compared to YA (Kanekar and Aruin, 2014). Similar EMG analysis during the grasp-lift-replace task may provide a deeper understanding of the muscular mechanisms that underpin anticipatory responses in YA and OA (Kimpara et al., 2020).

2.8 Summary

This chapter has outlined the key terminology and variables used to evaluate grasping. Research exploring grasping has shown healthy individuals initially anticipate the GF and LF required to lift an object, based on the objects visual properties (Bleyenheuft and Gordon, 2014) and previous lifts (Witney and Wolpert, 2007). Once the object has been lifted, subsequent (reactive) adjustments in GF and LF are made based on sensory information (Bracewell et al., 2003). Research has indicated OA still possess anticipatory and reactive control mechanisms, but their responses may not be as fine-tuned as YA (Cole and Rotella, 2001; Danion et al., 2007). There is growing evidence that muscular control of upper limb tasks are organised in a synergistic fashion – where groups of muscle are coordinated to simplify the control of movement (Santello et al., 1998; D'Avella et al., 2006), but to date, there has been little research exploring muscle activity specifically during a grasp-lift-replace paradigms. Future research exploring grasping in OA needs to explore anticipatory and reactive mechanisms underpinning grasping, with consideration for bimanual tasks, given the lack of current research and their use during ADL (Cole, 2009). Analysing the muscle synergies present in YA and OA grasping may also provide a greater insight into the changes in anticipatory and reactive control that occur as a result of age.

Chapter 3 – Designing Tools to Measure Grasping

3.1 Introduction

Chapter one discussed the motor decline that occurs as a function of ageing and its subsequent impact on performing activities of daily living (ADL). Chapter two focused on the motor control of grasping, the kinematic and kinetic parameters observed during grasping, and changes observed as a function of ageing. Chapter two concluded by highlighting the gaps in the current literature surrounding bimanual grasping and better understanding anticipatory and reactive grasping in older adults (OA). To investigate these research questions a custom-built tool is required – this chapter covers the background literature needed to build such a tool.

3.2 Tools for measuring grasping

Questionnaires, functional tests and observation can all be used to measure one's ability to perform ADL and grasping tasks (Wiener et al., 1990; Platz et al., 2005). Functional tests used to assess upper limb function and grasping include the Action Research Arm Test, Fugl-Meyer Assessment and the Grasp and Release test. These tests offer high levels of between-test agreement (rho > 0.92) and good levels of test re-test reliability (rho > 0.95) in clinical populations (Platz et al., 2005). However, it is common for individuals to score well in these tests and still complain of clumsiness when performing fine manipulative tasks (McDonnell et al., 2006). Additionally, questionnaires and functional tests can grade performance but are unable to explain the mechanisms that are responsible for poor grasping.

Grasp-lift-replace paradigms have proven useful in uncovering changes in force profiles used by OA when grasping and lifting objects (Cole, 1991; Cole and Beck, 1994; Parikh and Cole, 2012) and changes in anticipatory and reactive control within clinical populations during grasping tasks (Nowak and Hermsdörfer, 2003; Hermsdörfer et al., 2003; van Polanen and Davare, 2015). Thus, the grasp-lift-replace paradigm appears a useful approach for better understanding anticipatory and reactive control of grasping in OA when performing unimanual and bimanual tasks. Such research requires a device capable of measuring grip force (GF), load force (LF) and the position of the object during the phases of grasping – these tools are known as manipulanda (singular: manipulandum). The following section covers the considerations for building a manipulandum system capable of validly and reliably collecting GF and LF data. Later sections discuss the physical design properties of manipulanda needed to measure grasping in OA.

3.3 Validity and reliability of manipulandum systems

Despite GF and LF being integral to the study of grasping, few published papers report upon the validity and reliability of the manipulandum used to collect data. GF data is normally collected by a load cell positioned inside a manipulandum (Johansson and Westling, 1984; Cole, 1991; Parikh and Cole, 2012). As individuals apply a perpendicular force into the object, the load cell produces an increase in voltage which can be interpreted as a value of GF (Zatsiorsky and Latash, 2009). For this interpretation to be correct the load cell must be correctly calibrated and tested once inside the manipulandum. Published papers using bespoke manipulanda commonly mention the load cell make and model (Vermillion et al., 2015), contact surface (Johansson and Westling, 1984; Cole, 1991), but rarely discuss calibration methods used to determine validity and reliability pertaining to GF. Therefore, it can be assumed most papers rely on the manufactures' calibration of load cells, without further testing once the load cell is placed within a manipulandum. The following section draws upon the handful of publications that have discussed validity and reliability testing for manipulanda and handheld dynamometers (Bourbonnais et al., 2008; Lin et al., 2014).

3.3.1 Grip force

Criterion validity is the accuracy of a tool's measure compared to an already validated measure (Portney, 2020), this approach is commonly used to validate load cells used for measuring GF (Shechtman et al., 2005; Bourbonnais et al., 2008). Known weights are placed on top of the load cell, housed inside the manipulanda (Bourbonnais et al., 2008) or grip force dynamometer (Lin et al., 2014; Shechtman et al., 2005). By placing weights directly on top of a load cell, a static force can be measured via the load cell and compared to the known weight – giving an error reading between the two data points.

Bourbonnais et al. (2008) used five calibrated weights from 100 to 500g to validate the grip force measured by their manipulandum. The manipulandum was securely positioned with the load cell facing upwards. Data were collected with each mass positioned on top of the load cell, with a mean of the last 100 data points used for analysis. A similar process was used by Jaber et al. (2012), but using a hydraulic arm programmed to produce a set, static force, instead of calibrated weights. Shechtman et al. (2005) chose to suspend calibrated weights from their dynamometer to assess GF validity. In each case validity was calculated by performing a correlation between the mean values from the testing tools and the known force applied, across a pre-determined range of forces.

All three studies reported strong agreements between their measurement device and criterion measure, which indicates a range of possible procedures for validating load cells. The weight ranges selected to validate manipulanda to should cover the full range of grip forces anticipated from the target population (Bourbonnais et al., 2008). OA are well known for producing more GF when lifting, compared to YA (Cole, 1991; Diermayr et al., 2011). Previous research with manipulanda 160 - 400g in mass have shown OA produce GF ranges of 9 to 15N (Cole, 1991; Parikh and Cole, 2012). However, previous research in clinical populations have recorded GF levels up to 24 ± 2.3N when lifting a manipulandum with similar mass (312g). Consequently, testing of manipulanda for use in older populations should ensure the device is capable of valid and reliable measures of GF up to and possible above a range of 20N.

Reliability pertains to a tool's ability to consistently produce the same value when re-tested, it is calculated using a test of statistical variance (Portney, 2020). Both Pearson's correlation coefficient (r-value) and intraclass correlation coefficients (ICC) can be used to measure reliability (Shechtman et al., 2005). Reliability coefficients provide a value that can estimate the reliability present within a measurement device and give confidence about the variance seen in subsequent data collections. These estimates can assess reliability within a session (intra-session) – ensuring trial to trial variance is true variance from a participant and not error from the device. Reliability measures can also be measured between days (inter-session) – ensuring difference between participants tested on different days represents true differences between individuals and not measurement error. It is important to note, that there are no standardised rules when determining if a tool is valid or reliable enough, judgement should be taken when considering if values are suitable for its purpose. For example, previous grasping research has found peak GF values to be over double in OA (4.83 ± 1.49N) when compared to YA (2.25 ± 0.43N), with far greater variance in OA (Cole, 1991). Albeit less than ideal, if the goal is to separate the groups, a tool with up to 1N of error might be able to detect a mean different between these populations. As the research question requires more precision, or the effect size between groups becomes smaller, the validity and reliability of the device becomes more important (Shechtman et al., 2005; Portney, 2020).

Alongside static GF testing previous research has used healthy participants to perform lifts to ensure the GF waveforms represent a similar shape to that seen in previous studies. These have been accompanied with mean grip force values and standard deviations for the testing sample (Bourbonnais et al., 2008). Visual analysis of data is useful, as it displays many characteristics that are not captured by distilled values, such as peak GF and grip force to load force ratios. Nonetheless, caution must be taken when comparing findings to previous research. As previous studies vary considerably in the physical properties of manipulanda, such as mass (Johansson and Westling, 1984; Cole et al., 1998; Nowak and Hermsdörfer, 2006), set up position of the participant and lift height, all of which can affect grasping kinetics (McDonnell et al., 2005; Vermillion et al., 2015).

3.3.2 Load force

Load force (LF) is applied tangential to grip force and accelerates the object upwards, once inertia forces are overcome (figure 2.2). During the lift, LF can be calculated from the object's mass and acceleration, or by placing a load cell, within a manipulandum, capable of measuring the upward lifting force (Johansson and Westling, 1984; Hermsdörfer, 2009). During the grasp–lift–replace paradigm the majority of LF should be in a superior – inferior direction lifting the manipulandum upwards, but additional LF may be produced in the sagittal plane causing the object to move forward or backwards during lifting (Hermsdörfer et al., 2003).

Capturing LF components across both planes is challenging, without the use of a six DoF load cell (Vermillion et al., 2015), which comes at a considerable financial cost. The most commonly used approach to measure LF is to insert a uni-directional load cell within a manipulandum and only measure the vertical component of LF (Johansson and Westling, 1984; Cole, 1991; Blennerhassett et al., 2007). Another approach is to measure the acceleration of the manipulandum across all planes, using an accelerometer or optoelectronic system (such as Qualisys or Vicon) (Hermsdörfer et al., 2003). This second approach allows LF to be calculated at each point during the lift using the equation below. Where LF is equal to the mass of the object (M) times by a resultant acceleration vector including: vertical acceleration (A_Z), gravity (G) and acceleration in the sagittal plane (A_Y) (Hermsdörfer et al., 2003).

$$LF = M * sqrt((A_Z + G)^2 + A_Y^2)$$

Both approaches provide a measure of LF but have advantages and disadvantages – using a uni-directional load cell embedded within the manipulandum will allow the measurement of LF during the loading phase, before the manipulandum is lifted from the table. This is not possible when using an accelerometer. However, measuring LF using an accelerometer or optoelectronic system provides a more complete picture of LF once the object is airborne, capturing LF in vertical and sagittal planes (Hermsdörfer et al., 2003).

The procedures needed to test the reliability and validity of a manipulandum's ability to measure LF are dependent on the approach used. Embedding a load cell within the manipulandum to measure LF requires similar a testing protocol to that outlined for grip force validation (section 3.3.1), where known weights are used to find error values (Bourbonnais et al., 2008; Jaber et al., 2012). Whereas, accelerometers and optoelectronic systems rely on an accurate measurement of acceleration, and separately measuring the manipulandum mass (Hermsdörfer et al., 2003). Previous research has used optoelectronic systems to determine accelerometers' validity and reliability (Roe et al., 2018). Optoelectronic system, such as Qualisys or Vicon, have their own in-built calibration methods and are considered the gold-standard when measuring kinematics (Winter, 2009; Roe et al., 2018).

3.4 Manipulanda physical design

An object's size, shape, weight and material have all been shown to affect individuals' anticipatory planning during grasping (Gordon et al., 1991; Buckingham et al., 2009; Wing and Lederman, 2009) and the GF required to securely grip an object during transport (Johansson and Westling, 1984; Westling and Johansson, 1984; Cole, 1991). Consequently, careful consideration is required when designing manipulanda to assess grasping. The following sections synthesise the physical properties of manipulanda used to date to study grasping in healthy younger adults, OA and clinical populations suffering from sensorimotor loss. Recommendations are made for designing a manipulandum system to study bimanual grasping in OA.

3.4.1 Manipulanda mass

The mass of an object has a linear relationship to its weight (force = mass * acceleration), meaning a manipulandum with double the mass requires double the LF to hold the object stable in space, counteracting gravity. As manipulandum mass increases, GF increases in a linear fashion to account for the increased LF and to prevent the object slipping (Johansson and Westling, 1984). Pervious research in healthy grasping have used manipulanda with masses ranging from 100g – 1,000g (Westling and Johansson, 1984). Within ageing studies masses have ranged from 160g (Cole, 1991) to 400g (Danion et al., 2007). This lighter mass range used in ageing studies may reflect OA reduced upper limb strength (Carmeli et al., 2003a), thus if objects are too heavy OA may be unable to lift them using a precision grip. Development of a bimanual manipulandum system should take note of previous masses used. Building manipulanda within previous masses boundaries (160 - 400g) should safeguard against manipulanda being too heavy to lift and will allow a better comparisons between new bimanual findings and to previous unimanual results (Cole, 1991; Danion et al., 2007).

Many grasping studies alter the mass of manipulanda between trials, creating a need for participants to update grip force in a reactive capacity (Nowak et al., 2013). Historically, studies have added mass by attaching wiring and a basket of weight to manipulanda; hidden below the table surface (see appendix one for examples) (Johansson and Westling, 1984; Bleyenheuft and Thonnard, 2010). More recent designs have created manipulanda capable of housing additional mass within their casing (Nowak and Hermsdörfer, 2006; Vermillion et al., 2015). This progression in design no longer requires bespoke tables and wiring when testing participants, making manipulanda easier to transport outside lab-based locations (Hermsdörfer, 2009).

3.4.2 Manipulanda width

Increasing the width of manipulanda requires individuals to create a wider grip aperture (distance between thumb and finger tips) during the reaching phase (Paulignan et al., 1991).

Increasing object width from 50 to 90mm has been shown to cause slower reaching and less accurate digit placement in OA (Holt et al., 2013). OA have also been shown to drop objects when object width is increased to 90mm and combined with a slippery surface (the application of petroleum jelly). Indicating that the width of the contact points should be carefully considered when building manipulanda for OA. Aperture width has varied considerably in previous designs. Most researchers have used manipulanda with a smaller apertures: 17mm (Cole, 1991), 30mm (Westling and Johansson, 1984; Westling and Johansson, 1987), 35 mm (McDonnell et al., 2005), 40mm (Gorniak and Alberts, 2013), but more recent research has explored grasping with wider grip apertures: (74mm) in healthy OA (Parikh and Cole, 2012) and individuals with multiple sclerosis (90mm) (Iyengar et al., 2009). Indicating OA and populations with sensorimotor loss are able to grasp and lift objects up to 90mm in aperture. There is limited discussion within the literature as to why a given aperture has been selected. However, smaller apertures may help encourage a pinch (precision) grip between the thumb and forefinger. Whereas, the wider designs seen in recent years (Iyengar et al., 2009; Parikh and Cole, 2012) may better represent a grip aperture needed to grasp a cup or glass and offer increased ecological validity when applying grasp-lift-replace findings to ADL.

3.4.3 Contact point size & frictional properties

Manipulanda are designed with specific contact points (also known as plungers) that, when gripped, transfers the GF onto the load cell housed inside the manipulanda (figure 2.2). Contact points with a larger diameters (ø) afford individuals greater variations in how they apply their digits to an object (Wing and Lederman, 2009). For example, large, flat contact points (a jam jar lid ø) placed on opposing sides allow a manipulandum to be grasped with all four fingers and an opposing thumb. Conversely, small discs (1 pence piece ø) placed on either side force participants to use a single digit and opposing thumb (see appendix 1 for examples). The exact diameters used in previous research are not published. However, based on the images appearing within the literature, grasping research in populations suffering from sensorimotor loss, such as stroke and cerebral palsy (Bleyenheuft and Thonnard, 2010; Bleyenheuft and Gordon, 2014) use larger contact point diameters compared to research in young, healthy individuals (Johansson and Westling, 1984). Larger contact points potentially stop individuals with reduced motor function from missing the contact points and not being able to perform the task. Creating contact points that are too small can lead to individuals hooking their fingers under the contact points, rather than applying GF into the load cells (Wing and Lederman, 2009). Accordingly, manipulanda built for assessing grasping in OA need to ensure contact surfaces are large enough for all participants to complete the task and should create a design that prevents individuals hooking digits under the contact points.

The surface of the contact points mediates the coefficient of friction (CoF) created between the fingertips and object, affecting the relationship between GF and LF (Zatsiorsky and Latash, 2009). For example, a higher GF is required when gripping a slippery surface (lower CoF), compared to rougher contact surfaces (higher CoF). Despite OA consistently showing increased GF during dynamic and static grip force tasks (Cole, 1991; Gilles and Wing, 2003), OA have been shown to adapt to varying frictional properties just as well as YA (Gilles and Wing, 2003). Gilles and Wing, (2003) reported OA and YA show no difference in their ability to modulate GF to LF changes when gripping manipulanda with smooth PVC tape and rough sandpaper, indicating OA remain capable of detecting and adapting to varying frictions. Such similarities between YA and OA disappear when surfaces become very slippery – Holt and colleagues reported OA have trouble securely gripping objects with petroleum jelly coating the contact points (Holt et al., 2013). In consideration of these findings, the design of the contact point surfaces should avoid materials that are inherently slippery and aim to provide medium to high levels of friction during grasping and lifting (Gilles and Wing, 2003).

3.4.4 Portability of manipulanda

Manipulanda are commonly used to explore grasping strategies in populations suffering from sensorimotor deficits (Cole, 1991; Lang and Schieber, 2009; Iyengar et al., 2009; Bleyenheuft and Thonnard, 2010) these populations commonly suffer from reduced mobility, making travelling between locations difficult. Despite this clear issue, few manipulanda are built capable of functioning outside of a lab setting (Lin et al., 2014), see appendices one and two for examples of lab-based manipulanda. Reduced mobility is also associated with healthy ageing (Kang and Dingwell, 2009), consequently, when developing manipulanda to assess grasping in OA, the design should ensure the device is portable and able to reach OA that are unable to travel into a laboratory setting.

3.5 Summary

Manipulanda capable of measuring GF and LF provide great insight into the motor control of grasping (Gordon et al., 1994; Flanagan and Wing, 1997; Bleyenheuft and Thonnard, 2010), but such tool must be able to validly and reliably measure GF and LF (Bourbonnais et al., 2008; Jaber et al., 2012; Hermsdörfer et al., 2003). Careful consideration also needs to be given to the physical design of manipulanda – size, weight, contact point diameter and friction will all affect the grasping strategies used, and individuals' ability to successfully perform the grasping task (Johansson and Westling, 1984; Cole, 1991; Diermayr et al., 2011; Buckingham et al., 2016). When building a manipulandum system to study bimanual grasping in OA, similar masses to previous unimanual studies (160 - 400g) should be used to ensure the results are comparable (Cole, 1991; Danion et al., 2007). If possible, the manipulandum system should also be portable outside of a lab-setting to help reach OA who may have limited mobility and difficulty travelling to a laboratory-setting.

Chapter 4 – Building & Testing a Portable, Bimanual Manipulandum System

4.1 Introduction

As the world's population continues to live longer, there is an increasing need to keep older adults (OA) independent, for improved quality of life, but also to mitigate the financial burden associated with care for the elderly (Age UK, 2019). An integral part of maintaining independence is preserving the ability of OA to perform activities of daily living (ADL), however directly observing OA perform ADL does not indicate why they struggle to perform such tasks. A central skill in performing many ADL is the ability to grasp, lift and manipulate objects with one or two hands (Vieluf et al., 2015). Grasping can be more thoroughly analysed via grasp-lift-replace tasks using manipulanda that provide insight into the grip force (GF) and load force (LF) used by an individual when he or she grasps, lifts and replaces objects (Hermsdörfer, 2009). Subsequent analysis can be used to assess the efficiency of grasping strategies (Diermayr et al., 2011), the safety margin used when transporting objects (Cole, 1991) and explain mechanisms behind why an individual may have dropped an object during the lift (Johansson and Westling, 1984). Consequently, grasp-lift-replace paradigms can help explain differences between YA and OA grasping strategies, and potentially offer insight into how we can support OA perform ADL and keep them independent for longer.

Research to date has revealed OA use elevated GF profiles during initial stages of lifting and during the hold phase (Cole, 1991; Cole and Beck, 1994) and take longer to complete grasping tasks (Parikh and Cole, 2012), but research has predominantly focused on unimanual tasks (Cole, 1991; Cole et al., 1998; Parikh and Cole, 2012). Researchers have called for more bimanual research into grasping and ageing (Cole, 2009), as bimanual control is required for many ADL, such as dressing oneself and using a knife and fork (Lin et al., 2014), but bimanual research in grasp-lift-replace paradigms has been limited to date – potentially due to few bimanual manipulandum systems being developed. A second limitation within ageing and grasping research is the limited portability of manipulandum systems, meaning most testing occurs within a laboratory setting. This requires potential participants to travel into the laboratory in order to take part, which in-turn, may introduce a sampling bias into the data, with less mobile OA unable to take part.

A central requirement for any manipulandum system is the ability to validly and reliably measure GF and LF. Validity is defined as the ability of a tool to accurately and precisely measure a variable, with criterion validity specifically relating to the accuracy of a tool's measure compared to an already validated measure (Lin et al., 2014; Portney, 2020). Previous studies have used concurrent, criterion testing to validate new manipulanda (Shechtman et al., 2005; Bourbonnais et al., 2008). Known masses have been placed on load cells to assess the validity of grip force measures (Shechtman et al., 2005; Bourbonnais et al., 2008) and optoelectronic systems, such as Qualisys, have been used as criterion measures for kinematic testing of accelerometers (Roe et al., 2018). Manipulanda also need to be reliable in their measures of GF and LF – consistently producing the same values when re-tested (Portney, 2020). Reliability testing should be considered in two forms: i) within session reliability, to ensure trial-to-trial variance is true variance and not measurement error and ii) between session reliability, to ensure variance between participants tested in separate sessions is true variance and not measurement error. Both Pearson's correlation coefficients (r-value) and intraclass correlation coefficients (ICC) can be used to assess within session and between session reliability (Shechtman et al., 2005). Finally, the physical design of manipulanda also need careful consideration – the size, mass, contact point diameter and frictional properties can all affect the grasping strategy used (Johansson and Westling, 1984; Gordon et al., 1991; Holt et al., 2013). Previous research has shown OA can struggle when grasping wide, slippery objects (Holt et al., 2013), therefore the physical design needs to ensure individuals with wide-ranging levels of manual dexterity can successfully grasp and lift the manipulanda.

This study aims to develop a portable, bimanual manipulandum system that is suitable for studying bimanual grasping in OA. The experiment has four objectives: i) Assess the criterion validity of prototype manipulanda to measure grip force. ii) Assess the intrasession and intersession reliability of manipulanda to measure grip force. iii) Evaluate the criterion validity of accelerometers, placed within manipulanda to measure acceleration during the grasp-lift-replace task, compared to an optoelectronic system. iv) Use previous literature to design manipulanda with physical properties suitable for studying grasping in OA.

4.2 Methods

4.2.1 Manipulanda prototypes

Two manipulandum systems were created and tested, both were portable and capable of collecting unimanual and bimanual data. Protype 1 was a lower cost manipulandum system, that gathered all grip force and acceleration data with internal components. Prototype 2 offered a higher cost alternative, that gathered grip force data internally and used an external, 3D optoelectronic system to collect acceleration data. Prototype 2 was built as a result of the testing and shortcomings of Prototype 1. The physical design properties of Prototype 2 were also adapted as a result of the building and testing Prototype 1.

Prototype 1

Prototype 1 consisted of two manipulanda built from pre-existing components. The manipulanda body dimensions were 32mm (width) x 64mm (height) x 30.6mm (depth) built from Lego® blocks. The plunger surfaces were created by placing two further cylindrical Lego® bricks (16mm diameter, 11mm depth), extending 5mm outside the body dimensions, making the total grasping aperture ~64mm. Each manipulandum housed a 20N load cell (Make: Honeywell, model: FSG15N1A) that was used to capture grip force data, sampling at 200Hz, and a triaxial accelerometer (Make: SparkFun; model: ADXL335), also sampling at 200Hz. The grip force and acceleration data were processed using a 12-bit data acquisition card (National instruments MyRio 1900) and a custom-built program in Labview (v14).

Prototype 2

Prototype 2 consisted of two 3D printed, carbon-filled, nylon graphite manipulanda. The manipulanda dimensions were 40mm (width) x 110mm (height) x 50mm (depth). With the plunger surfaces extending a further 3 mm out each side, making the total grasping aperture ~46mm. The grip force plungers measured 30mm in diameter. Each manipulandum housed a 50N load cell (Make: Omega; model: LCM201-50) that were used to capture grip force data sampling at 200Hz. The grip force data was processed using a 16-bit data acquisition card (National instruments USB-6002) and a custom-built program in Labview (v14).

4.2.2 Grip force testing

Grip force testing included assessing the criterion validity of the load cells, housed within the manipulanda. The criterion measure was derived by placing known masses on the load cells and calculating the force exerted (mass (kg) * gravity (9.81m/s)). This was compared to the force measured by the load cells (Shechtman et al., 2005; Bourbonnais et al., 2008). The same testing protocol was used for Prototypes 1 and 2. The procedure, data processing and statistical analysis are documented in the following sections.

Procedure

The manipulanda were positioned horizontally, with the plunger surfaces facing directly upwards. The sensors were zeroed in this position, before known masses were then placed onto the plungers; with the corresponding weight measured (Lin et al., 2014). Data were captured for a 20 second period for each trial. The following six masses were used to assess validity and reliability (0.1, 0.2, 0.6, 1.6, 2.6 and 3.6kg). These masses provided data points spread across i) normal grip force values observed in healthy YA (Westling and Johansson, 1984) and ii) an upper range that adequately covered grip force ranges (9 to 15N) recorded in an ageing population (Cole, 1991; Parikh and Cole, 2012) and clinical populations suffering sensorimotor loss (24 ± 2.3N) (Iyengar et al., 2009). These masses were added in a randomised order, with each condition repeated three times (Shechtman et al., 2005). The full testing protocol was then repeated the following day to assess the inter-session reliability.

Data processing

Grip force data from Prototype 1 and 2 were collected in Labview 14 and filtered using a 4^{th} order low-pass Butterworth filter with a 12Hz cut-off before being exported to R Studios (v. 1.1.4) for statistical analysis.

Statistical analysis

The mean force error and percentage force error were calculated for all weight conditions to assess the criterion validity of grip force across the grip force ranges observed previously in ageing and grasping studies (Cole, 1991; Parikh and Cole, 2012). A regression analysis was also conducted between the criterion force (dependent variable) and the mean load cell force (independent variable). This provided a deeper insight into the relationship between the criterion measure and the protype measures. An output with an intercept = 0.00, beta = 1.00 and R^2 = 1.00 would indicate a perfect agreement between the two measures.

Within-session test-retest reliability was assessed using intraclass correlation coefficient estimates (ICC), 95% confidence intervals were calculated for each mass across the three trials using a two-way mixed-effects model with the absolute-agreement being reported (Koo and Li, 2016). To assess between-session reliability, mean values from the three trials were calculated for day one and day two. Intraclass correlation coefficient estimates and their 95% confidence intervals were calculated between the mean values of day one and day two to assess between-session test-retest reliability of the tool. The ICC function from the 'psych' package in R Studios (v. 1.1.4) was used to complete all testing.

4.2.3 Acceleration testing

Load force can be calculated as a product of a manipulandum's acceleration and mass (Hermsdörfer et al., 2003; Iyengar et al., 2009) (please refer back to chapter 3, section 3.3.2 for further details). Both Prototype 1 and 2 used this approach to calculate load force and therefore had to accurately measure acceleration during grasp-lift-replace task. Prototype 2 used a pre-validated optoelectronic system, however Prototype 1 used accelerometers housed within the left and right manipulandum. The following section details how the criterion validity of accelerometers in Prototype 1 were assess against the optoelectronic system.

Optoelectronic system

Previous research has indicated that 3D optoelectronic system provide a gold standard, criterion measure when testing the validity and reliability of accelerometers (Roe et al., 2018). A 10-camera (Oqus) Qualisys system (200 Hz) was used to collect acceleration data for lifting trials. Four Qualisys markers (12mm) were attached to each manipulandum to track the kinematics, with a 6 degrees of freedom model created for the left and right manipulandum in Qualisys.

Procedure

One healthy participant (25yrs old) completed the grasp-lift-replace task sat on a chair in front of a table – the chair and table were adjusted so that the table surface was level with their navel and their feet were flat on the ground; with their knees flexed at ~90 degrees. The manipulanda were placed 75% of shoulder width and 70% of maximum reach, as previous research has indicated that changes in shoulder and elbow flexion/extension can affect kinematic and kinetic parameters (Vermillion et al., 2015). Before the task began the participant's fingers and thumbs were cleaned with alcohol wipes to ensure the skin used to grasp the manipulanda was clean (Iyengar et al., 2009). The participant performed 10 lifts with the left and 10 lifts with the right manipulandum. The participant was instructed to pick up the manipulanda using the two circular plungers, using a precision grip. This grip was demonstrated by the researcher. Their task was to "grasp the manipulanda and lift them level with a target height placed in front of them (300mm height), and to hold the manipulanda as still as possible" (Johansson and Westling, 1984). After 10-seconds the researcher asked the participant to replace the manipulanda back on their starting markers. During each trial acceleration data were captured from Prototype 1 (accelerometers) and the criterion measure (optoelectronic system).

Data processing

Six degrees of freedom models were created in Qualisys for each manipulandum, a 21-frame, moving average filter was then applied before inferior / superior acceleration data was calculated in Qualisys for each manipulandum. Both accelerometer and Qualisys data were transferred to R Studios (v.1.1.4) where a 4th order low-pass Butterworth filter with a 12Hz cut-off was applied to both acceleration signals (Prototype 1 accelerometer data and Qualisys data).

Statistical analysis

Cross-correlations were run between the accelerometer and criterion measure for all trials, with no maximum time window – allowing for any temporal lag between the system. Peak correlation coefficients (r-value) were extracted for each trial to assess the agreement between the two signals. Peak acceleration values (minimum and maximum) were calculated for the accelerometer and criterion measure for all lifting trials, with absolute error and percentage error calculated to determine differences in magnitude between the two devices.

4.3 Results

Figure 4.1: The initial manipulandum design (Prototype 1) face-on (left) and side-on (right). Two circular plungers, with a small diameter, extend out of the manipulanda body encouraging a precision grip. Additional mass can be attached to the manipulanda via a screw thread under the plastic tube located beneath the grip plungers.

4.3.1 Prototype 1 results

Grip force validity

Testing revealed that masses above 0.6 kg could not be balanced on the grip force plungers. For this reason, grip force could only be tested across three mass conditions (0.1, 0.2 and 0.6kg). Table 4.1 shows the left manipulandum produced measurement errors of 2.6 to 5.5% across the different mass conditions. The right manipulandum showed greater accuracy, but still had errors ranging from 0.1 to 3.6%. Analysis of the data showed high levels of agreement for both the left; (intercept = 0.01, beta = 1.04, R^2 = 0.99, $p < 0.017$) and right (intercept = -0.11, beta = 1.02, R^2 = 1.00, $p < 0.004$) sensors across the three data point, but, validity could not be assessed above this force threshold.

Table 4.1: Mean error and percentage error for the left and right manipulandum load cells, used for capturing grip force in Prototype 1.

		0.1 kg	0.2 kg	0.6 kg	1.6 kg	2.6 kg	3.6 kg
Left manipulandum	Mean error (N)	-0.05	-0.22	-0.21	NA	NA	NA
	% error	-2.62	-5.55	-3.55	NA	NA	NA
Right manipulandum	Mean error (N)	0.07	0.06	0.01	NA	NA	NA
	% error	3.61	1.54	0.12	NA	NA	NA

Accelerometer validity and reliability

Results from the cross-correlation analysis between the accelerometer and optoelectronic data showed a poor agreement for both the left (r = 0.50 ± 0.07) and right (r = 0.50 ± 0.13) manipulandum. Table 4.2 shows the minimum and maximum acceleration values from the accelerometer and criterion measure during the grasp-lift-replace task. Accelerometer errors ranged from -24.5% to 6.9%, indicating a poor ability for the accelerometers to predict the magnitude of acceleration created during the grasp-lift-replace task.

Table 4.2: Peak (min and max) acceleration values recorded via accelerometers and the criterion measure for the left and right manipulandum of Prototype 1.

		Min acceleration (m/s^2)	Min percentage error (%)	Max acceleration (m/s^2)	Max percentage error (%)
Left manipulandum	Accelerometer	-1.41 ± 1.32	- 20.1	1.32 ± 0.35	- 24.5
	Criterion	-1.78 ± 0.25	-	1.75 ± 0.27	-
Right manipulandum	Accelerometer	-1.56 ± 0.48	- 14.0	2.14 ± 0.33	6.9
	Criterion	-1.90 ± 0.54	-	2.01 ± 0.31	-

4.3.2 Developments from Protype 1 to Protype 2

The initial testing with Protype 1 (figure 4.1) suggested the approach taken to create a bimanual manipulandum system was feasible, but the Prototype 1 needed a more accurate way of measuring acceleration and may benefit from some design alterations to help OA perform the grasp-lift-replace task. The design alterations made, error levels observed in Prototype 1 and implications are reviewed within the discussion (section 4.4). Based on the testing of Prototype 1, a new manipulandum system was developed – Prototype 2. Validity and reliability testing for Prototype 2 is documented below. Changes for Prototype 2 included: new load cells, new manipulanda casing, contact points and transitioning from capturing acceleration data with internal accelerometers to an external, pre-validated optoelectronic system (see section 4.2.1 for full details of Prototype 2).

4.3.3 Prototype 2 results

Grip force validity

Table 4.3 shows both manipulanda were accurate to within 1% of error across all mass conditions when compared to the criterion measure. Results from the regressions ran between the criterion measure and manipulanda show high levels of agreement for both the left; (intercept = -0.01, beta = 0.990, $R^2 = 1.00$, $p < 0.001$) and right (intercept = 0.00, beta = 0.992, $R^2 = 1.00$, $p < 0.001$) sensors. These findings indicate both manipulandum in Prototype 2 have high levels of accuracy when measuring forces ranging from ~1N to ~36N.

Table 4.3: Mean error and percentage error for the left and right manipulandum load cells, used for capturing grip force in Prototype 2.

		0.1 kg	0.2 kg	0.6 kg	1.6 kg	2.6 kg	3.6 kg
Left manipulandum	Mean error (N)	0.01	0.01	0.04	0.10	0.19	0.23
	% error	0.74	0.68	0.70	0.62	0.73	0.66
Right manipulandum	Mean error (N)	0.01	0.01	0.04	0.09	0.12	0.17
	% error	0.53	0.56	0.64	0.57	0.47	0.48

Grip force reliability

The ICCs computed to assess intrasession test-retest reliability indicated 'excellent' test-retest reliability for both the left (ICC = 1.0, $F(5,12) = 1.3e{+}07$, $p < 0.001$, CI lower = 1.0, upper = 1.0) and right (ICC = 1.0, $F(5,12) = 2.79e{+}6$, $p < 0.001$, CI lower = 1.0, upper = 1.0) manipulandum. The between day test-retest reliability was also shown to be 'excellent' for both the left (ICC = 1.0, $F(5,12) = 131{,}031$, $p < 0.001$, CI lower = 1.0, upper = 1.0) and right (ICC = 1.0, $F(5,12) = 161{,}834$, $p < 0.001$, CI lower = 1.0, upper = 1.0) manipulandum. The findings from the reliability and validity analysis indicate Protype 2 can provide a valid measure of grip force up to and above the grip force values expected in OA (Cole, 1991) and provides excellent levels of intrasession and between day reliability.

4.4 Discussion

This chapter documents the testing and development of a bimanual, portable manipulandum system, capable of accurately measuring grip force and load force. The following sections discuss the results in relation to the study objectives of: i) Assessing the criterion validity of prototypes to measure grip force. ii) The intra and inter-session reliability of the prototypes to measure grip force. iii) The criterion validity of accelerometers to measure acceleration during the grasp-lift-replace task, and iv) the use of previous literature to design the physical properties of manipulanda to assess grasping in older adults.

4.4.1 Grip force

Grip force validity

Grip force testing with Prototype 1 highlighted some limitations with the design. The device could not sustain masses equal or greater than 1.6kg. Although data could not be collected at higher mass conditions, the high R^2 value for both the left ($R^2 = 0.99$) and right ($R^2 = 1.00$) manipulandum suggests tests with higher masses might show similar levels of error up to the load cell's maximum testing capacity (20 N). Table 4.1 indicates that below a 1kg (9.81N) threshold there were low levels of absolute error, but this still translated into moderate values of percentage error across the left and right manipulandum (ranging from 0.1 to 5.6%). The different ranges in error between the left (-5.5% to -2.6%) and right manipulandum (+0.1% to +3.6%) would also create challenges in measuring true differences between left and right hands during bimanual grasping tasks. The load cells were always tested inside the manipulandum casing, meaning there is no conclusive evidence to suggest if this error was due to the load cell calibration or inability of the manipulandum's plunger and axle to transfer a perpendicular force onto the load cell, as is required to accurately measure grip force (Zatsiorsky et al., 2003). However, this data highlights the need for validating load cells with manipulanda, rather than relying on manufactures' calibration values.

Based on Prototype 1 testing, the second prototype was designed with a reduced tolerance between the manipulanda casing and grip plunger axle diameter, with the aim of keeping the axel perpendicular to the load cell and increasing the validity and reliability of grip force data collected. Along with these changes, the plunger surfaces were made larger and flatter to help calibrate at higher masses, and a new load cell was introduced; capable of measuring up to 50N. Table 4.3 shows that, as a result of these changes, Prototype 2 could be calibrated up to 3.6kg (~35.4N), ensuring the manipulanda could be tested above the peak grip force values recorded in OA performing similar tasks (Cole, 1991; Parikh and Cole, 2012). The measurement error was less than 0.7% for both manipulanda across all masses, indicating excellent levels of validity. This is confirmed by the results from the regression analysis, showing intercepts of -0.01 for the left and 0.00 for the right manipulandum, beta values of 0.990 for the left and 0.992 for the right manipulandum and R^2 values of 1.00 for both manipulanda when compared to the criterion measure.

Grip force reliability

Results from the ICC's for Prototype 2 showed excellent intrasession and between day test-retest reliability for both the left and right manipulandum. All findings for intrasession and between day showed ICC estimates of 1.0 for estimated values, and the upper and lower-bound confidence internals. These findings confirm Prototype 2 is well equipped to provide reliable grip force data over the course of multiple trials and across different days.

4.4.2 Load force

Load force can be calculated as a product of the manipulandum's acceleration and mass (Hermsdörfer et al., 2003; Iyengar et al., 2009). To accurately measure load force, the manipulanda must be able to precisely measure the acceleration during the grasp-lift-replace task. The third research objective within this study was to test the possibility of using an accelerometer housed inside the manipulanda (Prototype 1) to collect acceleration data. This approach was tested against an optoelectronic system, considered a gold-standard for measuring kinematics (Roe et al., 2018). Table 4.2 shows that the accelerometers, in both the left and right manipulandum, performed poorly when measuring the peak acceleration in both superior (max value) an inferior (min value) directions of motion compared to the criterion measure. The accelerometers generally under-estimated the peak accelerations created during the grasp-lift-replace task. Errors ranged from -24.5% to 6.9% (table 4.2) indicating a poor agreement between the peak amplitudes of the accelerometer and the criterion measure. In addition, the cross-correlation results show that, regardless of the two devices' amplitude, there was limited agreement between the two signals, with mean coefficients (r-value) of 0.50 for both the left and right manipulandum compared to the criterion measure. Load force data can be combined with grip force data to explain safety margins used during lifting (Cole, 1991), individuals' anticipatory control (McDonnell et al., 2006) and the economy of grasping strategies (Diermayr et al., 2011). Thus, the levels of error present within Prototype 1 (accelerometers) are not useful when considering the importance of load force in understanding grasping strategies used by OA. Based on these findings, the pre-validated optoelectronic system used for Prototype 2 will be used to collect acceleration data during future testing.

4.4.3 Design of physical properties

Mass

Pervious grasp-lift-replace experiments have used manipulanda with masses ranging from 100g to 1,000g (Westling and Johansson, 1984), with research in unimanual ageing studies masses from 160g (Cole, 1991) to 400g (Danion et al., 2007) have been used. The current manipulanda aimed to replicate similar mass values to previous unimanual ageing studies, so that data collected in a bimanual capacity could be compared to previous unimanual findings. Two masses of 200g and 400g were selected for the final manipulanda. These values fit in with previous ranges in ageing research (Cole, 1991; Danion et al., 2007) and allow for observation of how OA adapt grasping strategies for differing masses (200 to 400g) during bimanual tasks. The following section discusses how the physical design of the manipulanda integrated the capacity to vary mass.

Varying and occluding mass

The ability for manipulanda to change mass from one value to another has been critical in determining individuals' ability to update grip force based on sensory feedback – known as reactive control (Bleyenheuft and Thonnard, 2010). However, to elicit this response in a reactive manner, the true mass of the object must be occluded from the user, ensuring they only discover the true mass once the object is grasped. Frequently, this is achieved by attaching an additional mass via string or cables underneath the table surface (see appendix one for images).

However, this approach limits the portability of the manipulandum and reduces the ecological validity of the study, as in day-to-day situations changes of mass occur within the body of an object – consider an empty or full flask of liquid being lifted. Prototype 2 solved this problem by building upper and lower modular sections (see figure 4.2). The top half housed the load cell and grip force plungers whilst the bottom half had empty cavities that could be filled with varying mass. The two halves slide together with a dovetail joint, creating one seamless object. Two additional, identical lower casings were produced and filled with additional mass, meaning the lower half of manipulanda could be changed between trials to vary the total mass of manipulanda from 200g to 400g, whilst keeping the visual properties identical. This approach also increased the portability of the device, as there was no need to attach mass under a table or surfaces with additional strings or wires.

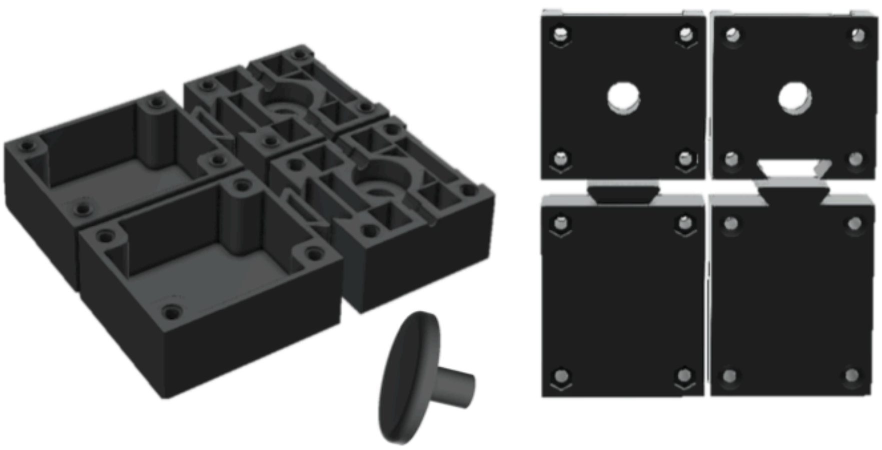


Figure 4.2: Cross-sectional design of the manipulanda casing. The left image shows the internal structure, the right image shows the external casing. The grip force plungers (lower middle) screwed directly onto the load cell, through the holes in the top of the casing.

Grasping aperture

Increasing the grasping aperture of objects leads to a longer reaching phase, and less accurate digit placement in OA (Holt et al., 2013), but little is known about how varying grasping aperture affects subsequent grip force control. Previous unimanual manipulanda used in ageing studies have encompassed a range of apertures from 17mm (Cole, 1991) up to 74mm (Parikh and Cole, 2012) (see appendix two for a visual guide of grasping apertures), however no studies have documented the effect of varying grasping aperture on OA's grip force control. Based on the limited data available for how aperture would affect grip force control in an older population, the current manipulanda favoured an smaller aperture, to ensure all OA could securely place their digits and complete the lifting task (Holt et al., 2013). The design also aimed to mirror apertures used in previous unimanual ageing studies (Cole, 1991; Parikh and Cole, 2012) to ensure findings were comparable. However, the minimum aperture was limited by the width of the load cell used and the thickness of the manipulanda casing. These considerations led to a final grip aperture of ~46mm for Prototype 2, this was the smallest aperture that could be created whilst housing a 50N load cell.

Contact points design

Previous manipulanda have employed varying contact point diameters (Ø) (see appendix one for small and large examples – exact diameters not published) (Johansson and Westling, 1984; Bleyenheuft and Thonnard, 2010), interestingly this metric is rarely mention or discussed in the literature. Prototype 1 incorporated small contact point diameters (~16mm Ø), mirroring designs from Cole (1991) and Westling and Johansson (1984), this design offered a restricted set of affordances, forcing participants to use a single digit on each contact point. However, pilot testing revealed that this small surface area led to some individuals hooking additional digits under the contact surfaces and also making additional contact with the manipulandum's body, meaning not all grip force data was captured by the load cell. Based on this testing the contact points were increased in size to 30mm Ø for Prototype 2, in addition, the edges of the contact points were bevelled (figure 4.3). The bevelled edges reduced the ability for individuals' to create additional friction using the edge of the contact points, as previous research has shown the use of angled contact points can affect grip force to load force ratios (Wing and Lederman, 2009).

Figure 4.3: The final design of the contact points, with the bevelled edges to reduce additional friction created when participants contact the edge of the contact surface.

Manipulanda body dimensions

With rare exception (Bourbonnais et al., 2008), previously designed manipulanda have given limited consideration to the visual properties of manipulanda. Most are designed with little structure besides the contact points and load cell (see appendix one and two for examples). Previous research has shown that individual's predict the heaviness of an object based on its visual properties (Buckingham, 2014), furthermore the visual properties affect the anticipatory grip response (Cashaback et al., 2017). Given these assertions the current design aimed to produce a simple casing to represent the visual properties of an everyday object. The design aimed to create an object size that was visually representative of its lower mass (200g), this was achieved by building manipulanda where the casing and load cell required little additional mass to achieve the 200g value. By inference, when the manipulanda mass were increased to 400g, with additional mass, the visual properties did not match the expected mass and the participant would underestimate the true weight of the object. Previous research has illustrated this underestimation is not long-lasting, with individuals soon updating their internal model and anticipatory response (Witney and Wolpert, 2007). The main aim of this thesis was not to explore the size-weight illusion, but rather to assess how YA and OA could update their anticipatory and reactive response, therefore this topic needed careful consideration within the design process. The final design dimensions for the manipulanda bodies were 40mm (width) x

110mm (height) x 50mm (depth). Figure 4.4 shows the final manipulandum body dimensions without the contact points (left) and the manipulanda setup for testing (right).

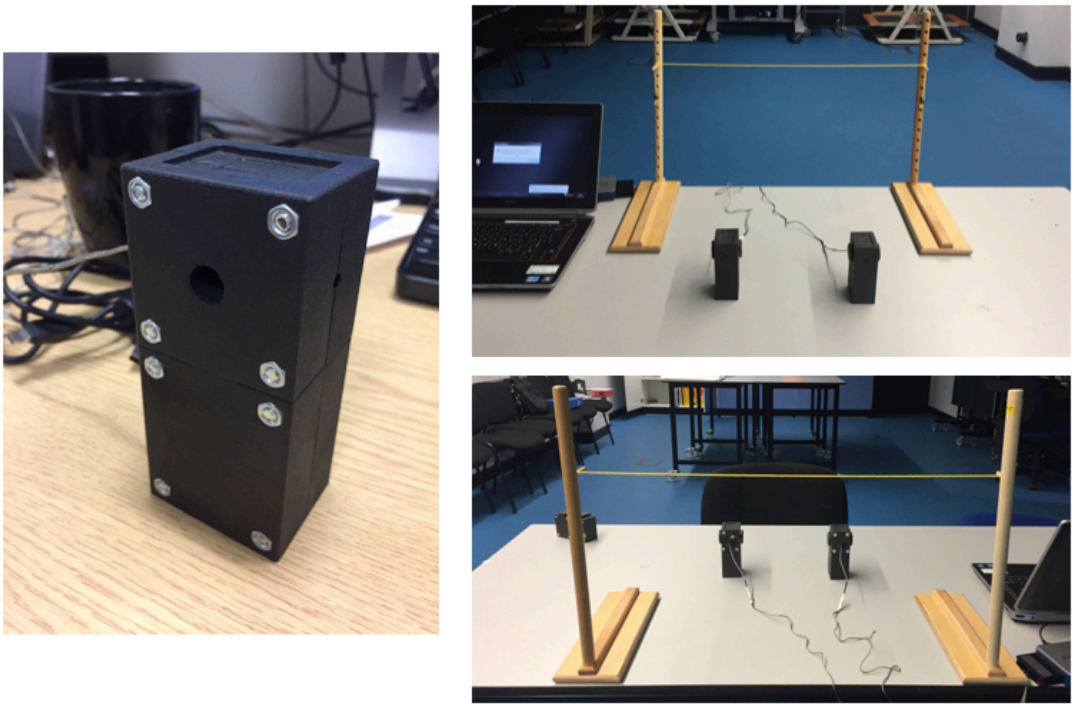


Figure 4.4: Left – the final manipulandum body (Prototype 2). Right – the final manipulanda setup for testing, from the participant's view (upper) and face-on to where the participant would be sat (lower).

4.5 Conclusion

This chapter documents the development and testing of a bimanual, manipulandum system for assessing grasping in OA. The testing has demonstrated the final design (Prototype 2) provides a valid and reliable system to measure of grip force. Both left and right manipulandum showed less than 1% error across forces ranging from ~1N to ~36N and provide excellent intra-session and inter-session reliability. Based on previous research, this range should adequately cover the upper grip force ranges (9 to 15N) previously recorded in ageing populations performing similar tasks (Cole, 1991; Parikh and Cole, 2012). By employing a pre-validated optoelectronic system, the final design also provides a valid way to capture acceleration data, and subsequently measure load force (Hermsdörfer et al., 2003). This approach is less portable than in-built accelerometers used in Prototype 1 but offers increased accuracy. The physical design of the final manipulanda considered previous research to ensure the grip aperture is appropriate for OA to successfully perform the task (Cole, 1991; Parikh and Cole, 2012; Holt et al., 2013). Consideration was also given to the masses used in previous unimanual grasping studies with OA (Cole, 1991; Danion et al., 2007), to ensure results found in this thesis are comparable. The outcome of this study is a portable, bimanual tool that can provide valid and reliable measures of grip force and load force to assess grasping in younger and older adults.

Chapter 5 – General Methods

5.1 Introduction

Many of the methods and procedures are common to experiments two and three (chapters 6 and 7). To avoid repetition, key procedures and methods used are documented in this chapter. Any methodological differences will be presented within the relevant study chapter.

5.2 Ethical approval

For all participants ethical approval was gained from the Faculty of Biological Sciences Research ethics committee, University of Leeds (REF: BIOSCI 14-018). All participants in the study gave informed consent prior to inclusion within the study.

5.3 Participant recruitment & selection

Posters were placed within the university, at local community centres and golf clubs to help recruit participants within the required age ranges. When potential participants made contact with the researcher, they were sent copies of the information letter and consent forms.

5.4 Participant inclusion & exclusion

All participants who took part in the studies had no known musculoskeletal or neurological conditions that would affect manual dexterity; and all had normal or corrected vision. The inclusion criteria for the younger adults' group were individuals aged between 18 and 30 years old on the day of testing. The older adults' group inclusion criteria were adults aged 60 years of or above on the day of testing for experiment two, with no maximum age. The lower boundary for older adults was extended to adults aged 50 years of age or older on the day of testing for experiment three. Two older adults took part in the testing but were unable to functionally complete the task due to a limited cognitive capacity. When this became apparent, the sessions were cut short and their data was not processed or used for analysis.

5.5 Overview of data collection & analysis

The following sections details how data were collected and processed for all participants in experiments two and three (chapters 6 and 7). Any additional steps carried out will be detailed within the appropriate section within chapters six and seven. The experiment consisted of three part: i) A grasping-lift-replace task, with a bimanual and unimanual components assessing both hands (ND and D) and varying object mass (Johansson and Westling, 1984). ii) Slip tests, to ascertain grip force rates at which slipping occurred (Cole, 1991). iii) Collection of biometric data including: assessment of maximum pinch force, cutaneous sensitivity and manual dexterity.

5.5.1 Grasp-lift-replace task

Task design

All participants took part in a series of grasp-lift-replace tasks. There were six conditions that were performed in a blocked, randomised order to mitigate for any learning effect, with each condition consisting of 10 consecutive repetitions. Lifts were performed under three conditions: i) non-dominant hand (ND), ii) dominant hand (D) and iii) bimanually (BM). These three conditions were repeated with two object masses: i) light (200g) and ii) heavy (400g), making a total of 60 trials (see table 5.1).

Table 5.1: The six grasp-lift-replace conditions performed by all participants. The conditions (each row) were block randomised between participants.

Trial number	Condition	Hand	Mass
1 – 10	Unimanual	Non-Dominant	Light
11 – 20	Unimanual	Dominant	Light
21 - 30	Bimanual	Both	Light
31 – 40	Unimanual	Non-Dominant	Heavy
41 – 50	Unimanual	Dominant	Heavy
51 - 60	Bimanual	Both	Heavy

Before the task began all participants' fingers and thumbs were cleaned with alcohol wipes to ensure the skin used to grasp the manipulanda were clean (Johansson and Westling, 1984). Subjects sat on a chair in front of a table, the chair and table were adjusted so that the table surface was level with their navel and their feet were flat on the ground, with their knees flexed at ~90 degrees. For each participant the grasping task was normalised by placing the manipulanda 75% of shoulder width and 70% of maximum reach, as previous research has shown gross changes in shoulder and elbow flexion/extension can affect grip force – load force coordination during lifting (Vermillion et al., 2015). Each participant was instructed to pick up the manipulanda using the two circular plungers, using a precision grip. This grip was demonstrated by the researcher. Their task was to "grasp the object(s) and lift them level with the target height (line of string) placed in front of them (300mm height), and to hold the objects as still as possible" (Johansson and Westling, 1984). After a 10-second period, the researcher asked the participant to replace the object(s) back on their starting positions (figure 5.1).

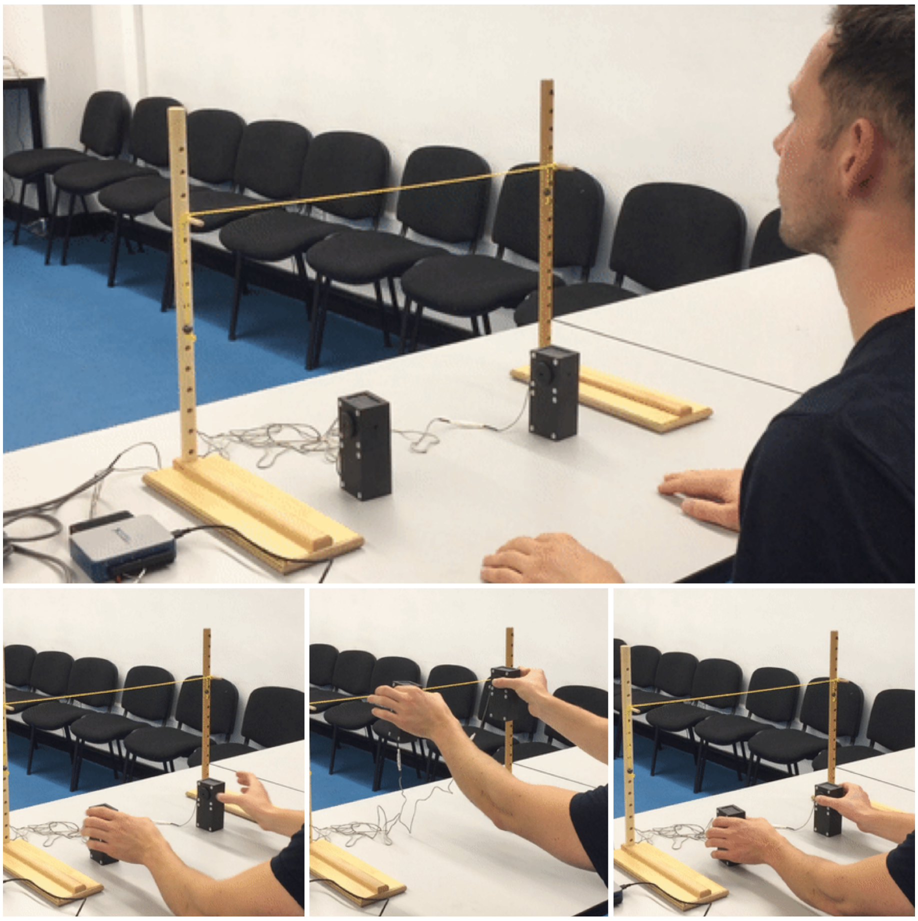


Figure 5.1: The phases of the grasp-lift-replace task – top: start position for each trial, bottom left: the initial grasp of the manipulanda, bottom middle: manipulanda raised to target height, bottom right: manipulanda replaced back on their starting locations.

Once the main lifting tasks were completed (table 5.1) participants performed the slip tests shown in table 5.2. Each slip test was performed three times, with the mean value taken from the three trials. The order of the slip tests were block, randomised between participants. Participants were instructed to hold the objects a few centimetres above the table, maintaining a steady hand position, and slowly reduce their grip force until the object slipped from their hand. The point of the slip, and subsequent slip force was determined post-hoc during data analysis by visually inspecting the objects position and acceleration curves (Johansson and Westling, 1984; Gorniak and Alberts, 2013).

Table 5.2: The four slip tests performed by each participant.

Trial number	Condition	Hand	Mass
1 – 3	Unimanual	Non-Dominant	Light
4 – 6	Unimanual	Dominant	Light
7 – 9	Unimanual	Non-Dominant	Heavy
10 - 12	Unimanual	Dominant	Heavy

Apparatus

A custom-built bimanual, manipulanda system, detailed in experiment one (chapter 4) was used throughout the grasp-lift-replace task and slip testing. The two manipulanda were made from Carbon-filled nylon graphite (casing and plunger surfaces). The manipulanda dimensions were 40 mm (width), 110 mm (height) 50 mm (depth). With the plunger surfaces extending a further 3 mm out each side, making the total grasping aperture ~46 mm. The grip force plungers measured 30mm in diameter. Each manipulandum contained a 50 N load cell (Make and model: Omega LCM201-50) that was used to capture grip force data at 200Hz. The grip force data was processed using a 16-bit data acquisition card (Make and model: National instruments USB-6002) and a custom-built program in Labview (v14). Four 12mm Qualisys markers were attached to each manipulandum to track the object kinematics. These markers were tracked using 5 or 12 Qualisys camera setups (depending on location: lab = 12 cameras, off-site = 5 cameras), with the capture frequency set to 200Hz. Both 5 and 12 camera setups produced calibration error values consistently below Qualisys' recommendations of 1.0mm (Qualisys, 2011). Data capture for the manipulanda and Qualisys systems were time-synced using an external trigger.

Data processing

Six degrees of freedom models were created in Qualisys for the left and right manipulandum, allowing their acceleration (x, y, z) and position (x, y, z) data to be extracted for further analysis. This data, along with grip force data from the manipulanda were export for subsequent analysis in R Studios (V. 1.1.46). Load force was calculated from the objects' mass times a product of the acceleration (vertical and sagittal) plus gravity (Nowak et al., 2001; Hermsdörfer et al., 2003; Hermsdörfer et al., 2008) as follows:

$$LF = M * sqrt((A_Z + G)^2 + A_Y^2)$$

Where 'M' is the object mass (200 or 400g), 'A_Z is the vertical acceleration, 'A_Y' is the acceleration in a sagittal plane, 'G' represents gravity (9.81) and 'sqrt' notion represents finding the square root. Grip force (GF) and load force (LF) data were then filtered using a 4^{th} order low-pass Butterworth filter with a 12Hz cut-off.

Temporal variables

The following temporal parameters were calculated: i) loading time, determined as the timepoint of first contact (GF > 0.1N) to the beginning of transport phase; ii) transport phase began when the object moved > 0.5mm above table surface, iii) stable phase began when velocity returned to < 0.001m/s after transport, iv) replace phase began when the object velocity > 0.001m/s after the stable phase and v) release began when the object returns to < 0.5mm of table surface and finished when GF returned below 0.1N.

Kinematic & kinetic variables

Peak GF and peak LF values were calculated as the maximum values reached within the first 5 seconds after initial contact, the subsequent times taken to reach peak GF and LF were also collected. Grip force to load force ratios (GF:LF) were calculated by dividing the GF by the LF (Johansson and Westling, 1984). A mean GF:LF value was calculated for the first 1 second (200 frames) of the transport phase (GF:LF start), and a second value taken 5 to 8 seconds into the lift during the stable phase (GF:LF stable). Three other variables were extracted from this 3-second section during the stable phase: i) Mean hold height was calculated as the mean height the manipulanda were above their initial starting position. ii) Path length was calculated from the frame-to-frame change in vertical-position for the manipulanda. The sum of squares was then taken to give a total vertical path length the manipulanda had moved during this timeframe. iii) Safety margin was calculated as the mean GF during the stable timeframe, minus the slip test value. Unique slip test values were calculated for each hand (ND & D) and mass (H & L) for each participant.

Finally, a cross-correlation was performed on the change in grip force (ΔGF) and change in load force (ΔLF) over the first 800ms of the transport phase to assess the dynamic relationship between GF and LF signals during anticipatory control (Duque et al., 2003; McDonnell et al., 2005). This method consists of searching for the largest correlation coefficient between the two signals by shifting one signal with respect to the other (Duque et al., 2003). The peak correlation coefficient (r-value) and time-shift at which it occurred (in milliseconds) were extracted for analysis. A negative time-shift indicated that the peak correlation occurred when GF leads LF, see figure 5.2 for example data.

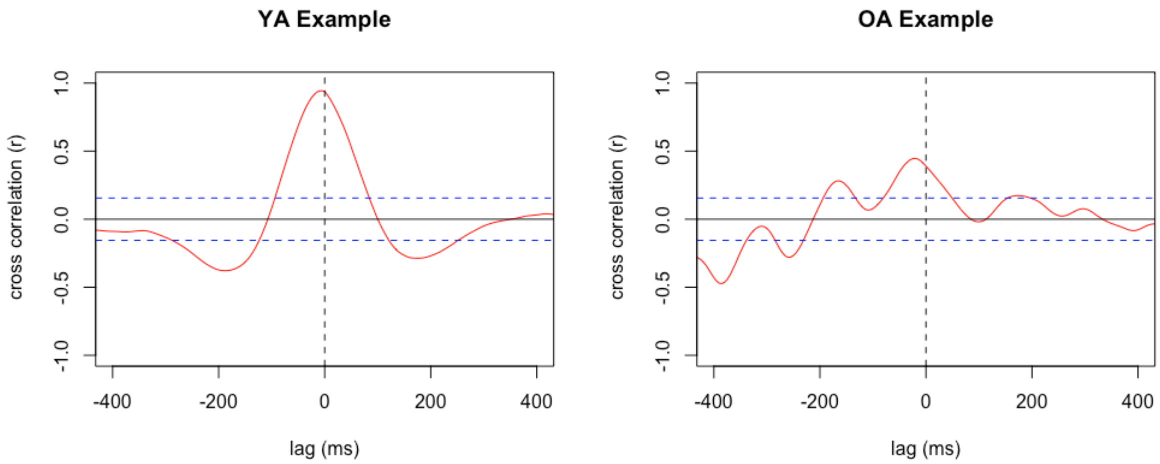


Figure 5.2: Example cross-correlation data from a YA and OA participant. The peak value found represents the max cross-correlation for a given trial. The time lag of the peak value represents time-shift of the GF and LF to obtain a given correlation value; a minus time-shift represent GF scaling before LF.

For all temporal, kinematic and kinetic variables means values were calculated by averaging across the 10 trials performed by each participant within each condition.

5.5.2 EMG data collection

EMG data were collection bilaterally from the Anterior Deltoid (Ant Del), Flexor Carpi Radialis (FCR), Extensor Carpi Radialis (ECR) and Abductor Pollicis Brevis (APB) using eight Delysis Trigno™ sensors. These muscles were select based on previous research highlighting their role in the grasp-lift-replace action (Maier and Hepp-Reymond, 1995; Lemon et al., 1995; Hashemi Oskouei et al., 2013) (see section 2.7 for further details). Skin was prepared by shaving the area and wiping away surface debris with alcohol wipes to improve the conductivity and reduce the signal to noise ratio (Hermens et al., 2000). Standard-sized Tringo™ sensors (sampling at 2,000Hz) were placed on the Ant Del, FCR, ECR and mini Delysis Trigno™ sensors were placed on the APB. EMG data were captured using a Delysis Trigno™ system which automatically applies a high cut-off of 450Hz and a rolling low cut-off of 20Hz. Data were time-synced and stored with kinematic data in Qualisys (v.2.17); using an external trigger. Raw EMG data were exported from Qualisys into R Studios (v.1.1.46) for processing and further analysis.

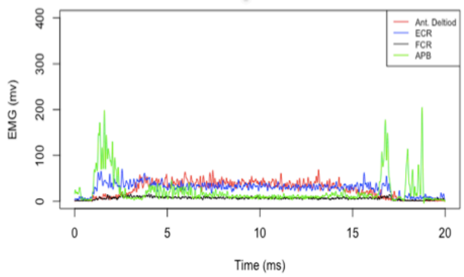
EMG data processing

The EMG data for each trial were digitally, full-wave rectified, low-pass filtered (10Hz cut-off, 4^{th} order Butterworth, zero-phase distortion; R Signals package, filtfilt function) and down-sampled to 200Hz to align with kinetic and kinematic datapoints. In some cases, artefacts appeared within the APB data, where the sensor may have partially lost contact with the skin. All trials were visually scanned, with affected trials removed from further analysis (D'Avella et al., 2006). EMG data were normalised against peak EMG activity observed during the grasping task (all 60 trials), for each individual and subsequent muscle, giving each muscle a normalised value between 0 and 1 (Hug et al., 2010; Delis et al., 2013). For each trial, data were time-sliced into two parts for further analysis: i) dynamic phase – from the point of first contact to the beginning of the stable phase, and ii) stable phase – from the beginning to the end of the stable phase. All phases were time-normalised to 101 datapoints to ensure equal temporal weighting across participants and conditions for the subsequent analysis.

EMG analysis

EMG data for all trials (n = 60) and participants were concatenated to form one matrix (4 muscles * n datapoints) see figure 5.3. Non-negative matrix factorisation (NMF) analysis was carried out using the NMF package (v.0.21.0) in R Studios, applying the default 'Brunet' algorithm, where the existing EMG dataset (V) was estimated by two new matrices (W and H) whereby V ~ W * H. A rank of three was selected to represent the following functional goals the selected muscles were expected to perform during grasp-lift-replace task: i) flexion of the shoulder required to elevate the object (Ant Del), ii) stabilisation of the wrist during the grasp and lift (FCR & ECR) and iii) the application of grip force onto the object (APB) (Cole and Abbs, 1988; Maier and Hepp-Reymond, 1995; Holmes et al., 2015). Each NMF analysis was ran 30 times to find the optimum local minima (Brunet et al., 2004).

Data
1) Normalised to max EMG
2) Cut to dynamic/stable phase phase
3) Normalised to 101 datapoints
4) Concatenated onto all other trials



Single trial of rectified and filtered EMG data

Group	Participant	Condition	Trial	Ant Del	ECR	FCR	APB
YA	1	1	1	EMG data	EMG data	EMG data	EMG data
			2				
			3…				
		2					
		3…					
	2						
	3…						
OA							

Figure 5.3: Left-hand image shows a single trial of EMG data post filtering and rectification. Each trial was then normalised to the max EMG amplitude, cut, time-normalised to 101 datapoints and concatenated to all other trials. The data formed one large matrix (right) for NMF analysis which was labelled with trials (1-10), conditions (n = 6, see table 5.1), participants and group. Separate matrices were formed for the: i) dynamic phase – from the point of first contact to the beginning of the stable phase and ii) stable phase – from the beginning to the end of the stable phase.

The model coefficients (H matrix) were extracted to assess the invariant muscle synergies groupings (MS1, MS2, MS3). The basis values (W matrix) were extracted to assess the temporal weightings of MS1, MS2 and MS3 across participants and within-subjects factors of condition (UM and BM), hand (ND and D) and mass (L and H). Correlations were run between each muscle synergy i) MS1 – MS2 ii) MS2 – MS3 iii) MS1 – MS3) to assess the relationship between the muscle synergies during the grasp-lift-replace task, and how this varied between participants and within-subject factors of condition, hand and mass. The 'evar' function from the NMF package was used to assess how well the NMF model explained the variance of the original EMG dataset, with 1.0 indicating variance in the original dataset could be fully explained. This process was repeated for datasets taken from the dynamic and stable phases the grasping task.

5.5.3 Biometric tests

Pinch force

Maximum pinch force was measured using a dynamometer (Jamar Plus Digital Hand Dynamometer). Participants created a pinch grip using their index, middle finger and opposing thumb, with the dynamometer placed in the same start location as the manipulanda, to standardise arm position between individuals. They were instructed to squeeze the dynamometer as hard as they could, whilst maintaining their hand posture, for a period of six-seconds. All subjects were encouraged verbally during the task (Santos et al., 2010). A one-minute rest was given before this process was repeated with the opposing hand. Both hands were tested three times, with the highest value for each hand taken as maximum pinch force.

Purdue Pegboard test

The Purdue Pegboard test has been used to assess manual dexterity in healthy adults, ageing populations (Desrosiers et al., 1995) and tracking changes in manual dexterity over time (Desrosiers et al., 1999). It is a robust test for assessing manual dexterity, with normative data for healthy older and younger adults. The Perdue Pegboard test includes sub-tests for assessing dominant, non-dominant and bimanual levels of dexterity, with all sub-levels of the test providing high levels of reliability ($r = .60 - .86$) (Tiffin and Asher, 1948) specifically when working with OA ($r = 0.66$ to 0.90) (Desrosiers et al., 1995). The test requires the participant to see how many pins they can place into the allocated holes within a 30-second time period. Each participant took part in three subsections of the Purdue Pegboard Test: dominant hand, non-dominant hand and bimanual, the assembly test was not used. The total number of pins placed within the pegboard were recorded for each subsection. In line with the manufactures (Lafayette Instruments) guidance, precise instructions were given to each participant, accompanied by a demonstration, and time to practice before each subsection of the test. This procedure was consistently followed with each participant. The instructions for right hand are given below:

"Pick up one pin at a time with your right hand from the right-handed cup. Starting with the top hole, place each pin in the right-handed row. (Leave the pin used for demonstration in the hole). Now you may insert a few pins for practice. If during the testing time you drop a pin, do not stop to pick it up. Simply continue by picking another pin out of the cup."

Semmes-Weinstein test

The Semmes-Weinstein test was used to assess cutaneous sensitivity in the thumb and fingertips. The testing kit includes 19 monofilaments of varying thicknesses. Each monofilament flexes under a specific force. The bending forces and subsequent categorisation for cutaneous sensitivity are shown in table 5.3 below:

Table 5.3: The Semmes-Weinstein monofilament size, target (bending) force and considered thresholds of function.

Evaluator Size	Target force in grams	Threshold
1.65	0.008	Normal
2.36	0.02	
2.44	0.04	
2.83	0.07	
3.22	0.16	Diminished light touch
3.61	0.4	
3.84	0.6	Diminished protective sensation
4.08	1	
4.17	1.4	
4.31	2	
4.56	4	Loss of protective sensation
4.74	6	
4.93	8	
5.07	10	
5.18	15	
5.46	26	
5.88	60	
6.10	100	
6.45	180	Untestable

The participant placed their palm facing up and fingers extended through a sheet to occlude their vision of the test and ensure detection was due to a cutaneous response. A total of eight testing sites (four per hand) were assessed for each participant: middle finger (31), index finger (21U and 21R) and thumb (11) (figure 5.4). For each test site the researcher began with the finest monofilament and pressed 3 times into the centre of the testing zone. The monofilament was pressed into the skin until the filament lightly flexed. If the participant felt the sensation created by the monofilament they were asked to respond with “touch” or “yes”. If there were no positive responses the researcher repeated the procedure with the next finest monofilament. The target force that was required to elicit a response was recorded for each zone. The sum force in grams was calculated for each hand for each participant to represent cutaneous sensitivity.

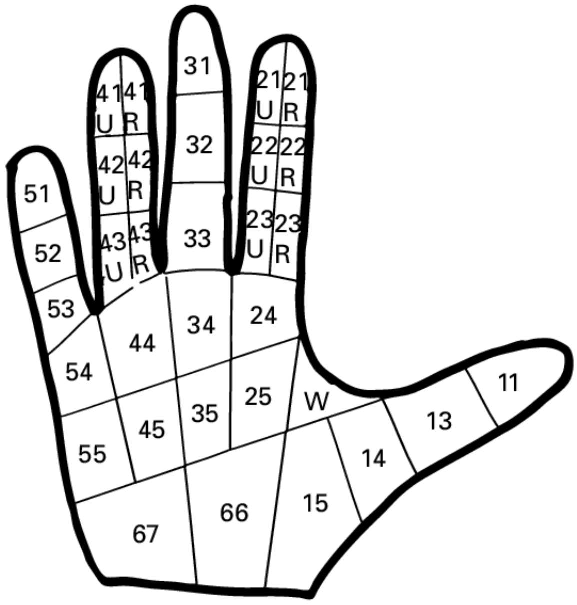


Figure 5.4: The numbered locations for each area of the hand for the Semmes Weinstein test. Testing zones 31, 21U, 21R and 11 were tested on each hand of participants.

Chapter 6 – Unimanual & Bimanual Grasping in Older Adults

6.1 Introduction

The ability to grasp, lift and transport objects is a skill required for older adults (OA) to perform activities of daily living (ADL) and maintain their independence (Murata et al., 2010). Some daily tasks, such as picking up a glass of water, require one hand to be used independently (unimanual), other tasks require a coordinated response from both hands simultaneously (bimanual), such as buttoning a shirt or carrying a plate of food (Vieluf et al., 2015). Both unimanual and bimanual grasping requires individuals to initiate the grasp by anticipating the object's mass, surface texture and subsequent motor action required (Gordon et al., 1991), known as anticipatory control. To achieve this individuals rely on an internal model of the task (Nowak et al., 2013), based on previous task experience (Witney and Wolpert, 2007). Once the object has been successfully grasped, sensory information can be compared to the initial task predictions and be used to update the motor commands sent to the upper limbs (reactive control) (Bleyenheuft and Gordon, 2014).

The majority of research examining grasping in OA has focused on unimanual control, despite the call for more bimanual research (Cole, 2009) and the application of bimanual grasping to ADL (Lin et al., 2014). Findings from unimanual grasping studies have shown OA have particular trouble grasping objects with a wide aperture and slippery surfaces (Holt et al., 2013). OA also show an increased time-period for completing the pre-loading and loading phases of the lift, regardless of the object's intrinsic characteristics (Cole, 1991). At a kinetic level, OA consistently show an increased grip force and safety margin when lifting objects (Diermayr et al., 2011; Cole, 1991; Cole and Beck, 1994). There is still uncertainty as to why OA use adaptive grasping strategies. Previous research has proposed these kinematic and kinetic changes could be compensatory mechanisms for OA having more slippery skin (Diermayr et al., 2011) and a lower coefficient of friction when grasping objects. Other researchers (Cole, 1991) have suggested the increased grip force and safety margin, seen in OA, is no more than a learned strategy to prevent the objected being dropped. A third theory proposes OA have a reduced capacity to scale grip forces to changes in load force (Danion et al., 2007), indicating reduced anticipatory control. However, current data surrounding this viewpoint is not conclusive, with researchers arguing for (Danion et al., 2007) and against

(Cole, 1991; Gilles and Wing, 2003) OA showing a decline in anticipatory control – see Diermayr et al. (2011) for a review of literature.

One potential reason for the disparity in explaining anticipatory grasping control in OA are the analytical approaches that have been used to date. Research in ageing and grasping has relied on a handful of simple variables (peak grip force, time to peak grip force, time to peak load force and safety margins) to distil the grip force and load force signals collected (Cole, 1991; Gilles and Wing, 2003). Albeit useful, these variables often rely on discrete data points, and do not fully capture the dynamic relationship between changes in grip force and changes in load force during anticipatory and reactive periods of grasping (Grover et al., 2019). Some grasping research has shown cross-correlation techniques between changes in GF (ΔGF) and changes in LF (Δ LF) are useful for examining anticipatory control within clinical populations (Duque et al., 2003; McDonnell et al., 2006). Modelling grasping adaptations into anticipatory and reactive control mechanisms has also provided a useful framework for synthesising the changes observed in grasping within clinical populations (Duque et al., 2003; McDonnell et al., 2006). Both a cross-correlation analysis and modelling data analysis into anticipatory and reactive stages of grasping control have yet to be applied to a grasp-lift-replace task with OA. This approach could shed more light on grasping changes observed in OA and provide a better understanding of why OA struggle to perform ADL.

Based on the aforementioned literature, the aims of this study are to: i) Explore muscular, kinematic and kinetic differences in grasping between YA and OA, across anticipatory and reactive stages of a grasp-lift-replace task. ii) Assess muscular, kinematic and kinetic differences across unimanual and bimanual grasp-lift-replace tasks performed by YA and OA. iii) Quantify differences in manual dexterity, pinch strength and cutaneous sensitivity between YA and OA.

6.2 Methods

6.2.1 Participants

Two groups of participants volunteered for the study, 20 YA (M = 22.2 ± 2.59yrs old; F = 14) and 20 OA (M =70.8 ± 7.42yrs old; F = 11). There were three left-handed participants in the YA group and two left-handed participants in the OA group, identified by the asking participants their preferred hand for performing ADL. All participants had no known musculoskeletal or neurological conditions that would affect manual dexterity, and all participants had normal or corrected vision. See (chapter 5, section 5.4) for more information on inclusion and exclusion criteria.

6.2.2 Procedure

All participants took part in the grasping and lifting tasks, involving both hands, two mass conditions and unimanual and bimanual components (see chapter 5, section 5.5.1 for full details). This was followed by a set of slip-tests and collection of biometric data: max pinch strength, Semmes-Weinstein monofilament test and Purdue Pegboard test. See the chapter 5, section 5.5.3 for full details.

6.2.3 Data analyses

Grasping variables

Data analyses were performed in SPSS (v22) with R Studio (v1.1.46) used to produce figures. Data were visually inspected using line plots (mean ± standard error) for each factor and group. Boxplots were also used to assess the spread of the data and identify outliers that might skew the model fitting process. Sixteen separate repeated-measures (one for each separate dependent variable), mixed mode ANOVAs were performed. The ANOVA models included one between subject factor; groups (younger adults (YA), older adults (OA)) and three within factors: 1) Condition, with two levels: unimanual (UM) and bimanual (BM). 2) Hand, containing two levels: non-dominant (ND) and dominant (D) and 3) Mass, with two levels: light (L) and heavy (H). Alpha levels were set to 0.05.

Levene's test of homogeneity was used to assess equal variance across groups, with Shapiro-Wilk tests were used to assess the normality of the model residuals. For Levene's and Shapiro-Wilk tests alpha was set to a level of 0.05. Where appropriate, the data were log-transformed to normalise the model's residuals. Welch's t-tests were used for post-hoc tests between groups and conditions (Ruxton, 2006; Derrick and White, 2016).

Biometric variables

Maximum pinch force and Semmes-Weinstein data were analysed using two separate mixed mode ANOVAs, with group (YA and OA) as a between subjects factor and hand (ND and D) as a within subjects factor. A mixed ANOVA was also performed on total Purdue Pegboard scores, as structured above, however the between subjects factor had three levels: D, ND and aggregated BM scores to assess group and hand differences in manual dexterity.

EMG variables

Mixed effects linear models were used to test statistical significance of the correlations ran on the temporal weightings of the NMF outputs (see chapter 5, section 5.5.2 for full details). Mixed effects linear models were selected to test between groups and across conditions as they are more robust dealing with datasets containing missing values (Zuur et al., 2010), caused by data removed due to EMG artefacts (see chapter 5, section 5.5.2). The models were structured to have a between fixed effect of group (YA, OA) and three within fixed effects 1) Condition, with two levels: unimanual (UM) and bimanual (BM). 2) Hand, containing two levels: non-dominant (ND) and dominant (D) and 3) Mass, with two levels: light (L) and heavy (H). All models contained participants as a random effect, nested within group, condition, hand and mass (Zuur et al., 2009; Harrison et al., 2018). The nlme package in R was used to perform all analysis (Pinheiro et al., 2020), once the models were built and tested, the ANOVA function was used to extract between and within factor differences. Where appropriate, Welch's t-tests were used for post-hoc tests between groups and conditions.

6.3 Results

The following section covers the statistical findings. Temporal aspects of lifting (loading, transport, stable, replace and release times) are followed by the kinematic variables (path length and hold height). Lastly, kinetic related parameters are covered (peak GF, time to peak GF, peak LF, time to peak LF, GF:LF at start, GF:LF ratio during the stable phase, safety margins, max cross-correlation and time-shift of max cross-correlation). To help visualise the findings, the raw, non-transformed data are always displayed for any group means and standard errors in text and/or in graphical displays. The kinematic and kinetic results are followed by statistical analysis of the biometric data and analysis of the EMG data.

6.3.1 Temporal, kinematic and kinetic results

Example lifts from a YA and OA are presented below in figure 6.1. Note the increased levels of GF in the OA example and relationship between GF and LF for the YA and OA throughout the lift.

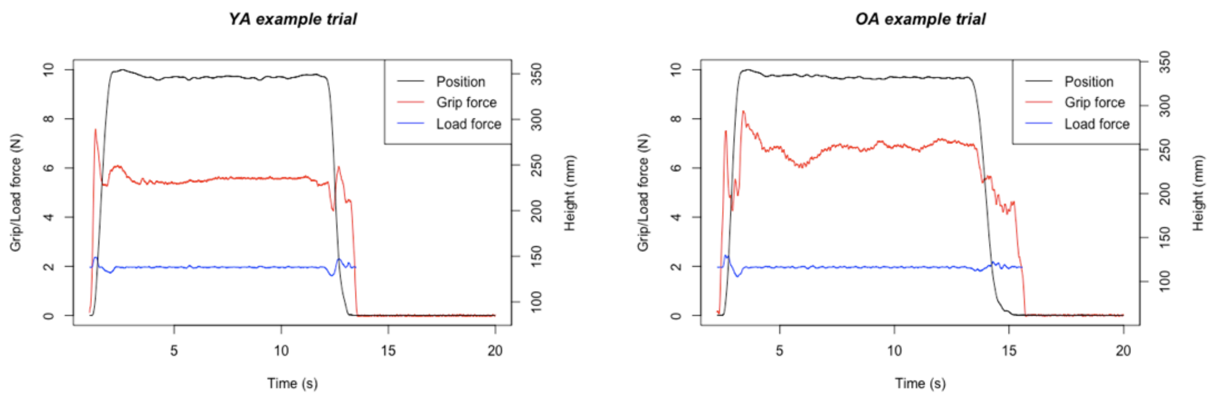


Figure 6.1: Example trials for YA and OA (unimanual, dominant hand, light mass). GF and LF data are presented on the left axis, with vertical position (black line) of the manipulandum on the right axis.

Loading time

A log transformation of loading time was calculated and used for analysis, as the raw data failed assumption testing for equal variance. The results showed a significant main effect of group; ($F(1, 38) = 9.55$, $p = 0.004$, $\eta 2 = 0.20$; YA = 0.41s; OA = 0.62s), condition ($F(1, 38) =$

134.6, $p < 0.001$, $\eta 2 = 0.78$; UM = 0.44s; BM = 0.59s), and mass ($F(1, 38) = 76.7$, $p < 0.001$, $\eta 2 = 0.67$; L = 0.44s; H = 0.60s), but no effect of hand (*F(1, 38) = 0.07, p = 0.79,* $\eta 2 = 0.00$; ND = 0.52 s; D = 0.51 s). No two, three or four-way interactions were present. In summary – loading time increased for OA compared to YA, BM conditions compared to UM and heavy masses compared to light (figure 6.2).

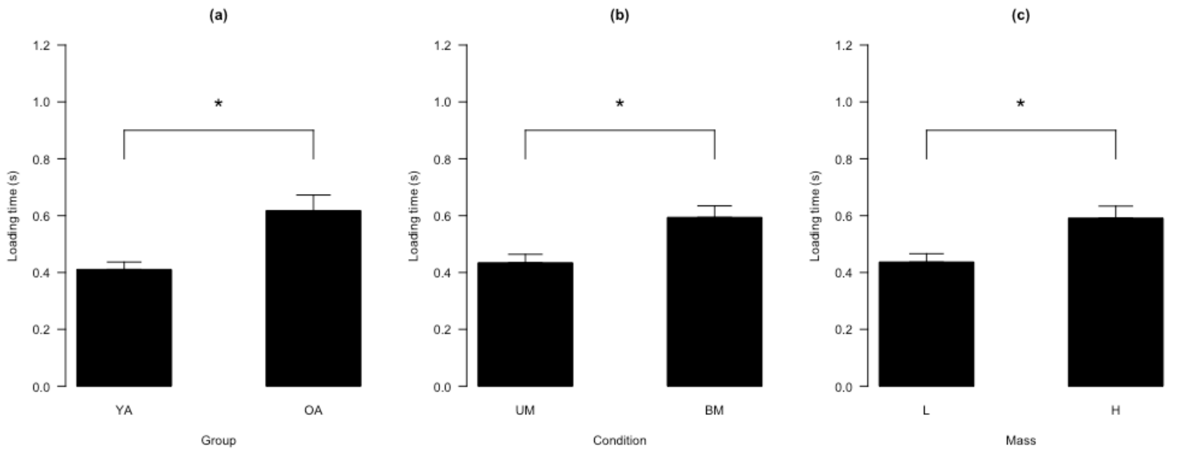


Figure 6.2: Mean loading time (± SE) for (a) YA and OA groups (b) UM and BM conditions and (c) L and H masses.

Transport time

Analysis of transport time revealed a significant main effect of condition ($F(1, 38) = 5.61$, $p = 0.02$, $\eta 2 = 0.13$; UM = 1.28s; BM = 1.33s) with an increased transport time for BM lifts, but no significant effect of group ($F(1, 38) = 0.12$, $p = 0.73$, $\eta 2 = 0.00$; YA = 1.29s; OA = 1.32s), hand ($F(1, 38) = 1.39$, $p = 0.25$, $\eta 2 = 0.00$; ND = 1.31s; D = 1.29s) or mass ($F(1, 38) = 0.06$, $p = 0.81$, $\eta 2 = 0.00$; L = 1.30s; H = 1.31s). A significant three-way interaction between group * condition * hand ($F(1, 38) = 4.78$, $p = 0.035$, $\eta 2 = 0.11$) was present, but subsequent analysis found no two-way interactions present between: group * condition ($F(1, 38) = 1.23$, $p = 0.28$, $\eta 2 = 0.00$), group * hand ($F(1, 38) = 0.75$, $p = 0.835$ $\eta 2 = 0.02$), condition * hand ($F(1, 38) = 3.79$, $p = 0.06$, $\eta 2 = 0.09$), group * mass ($F(1, 38) = 0.45$, $p = 0.51$, $\eta 2 = 0.01$), hand * mass ($F(1, 38) = 0.25$ $p = 0.62$, $\eta 2 = 0.01$) or condition * mass ($F(1, 38) = 0.007$, $p = 0.94$ $\eta 2 = 0.00$) so this interaction was not explored further.

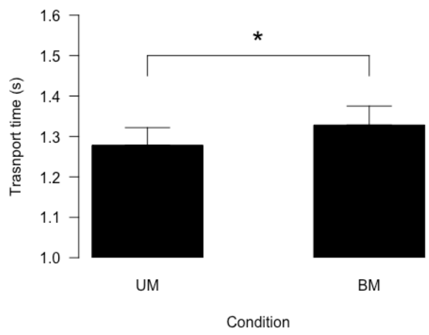


Figure 6.3: Mean transport time (± SE) for UM and BM conditions.

Stable time

No significant main effects were present for stable time. There was one condition * hand * mass interaction present ($F(1, 38) = 5.20$ $p = 0.03$, $\eta2 = 0.12$), but subsequent analysis found no two-way interactions present so this interaction was not explored further (see appendix 9.3 table 9.3 for further details).

Replace time

Analysis of replace time revealed a significant main effect of condition ($F(1, 38) = 48.1$, $p < 0.001$, $\eta2 = 0.56$; UM = 1.52s; BM = 1.66s), with an increased replace time for BM lifts, but no significant effect of group ($F(1, 38) = 0.00$, $p = 0.95$, $\eta2 = 0.00$; YA = 1.59s; OA = 1.59s), hand ($F(1, 38) = 1.24$, $p = 0.27$, $\eta2 = 0.03$; ND = 1.58s; D = 1.60s) or mass ($F(1, 38) = 1.15$, $p < 0.29$, $\eta2 = 0.03$; L = 1.58s; H = 1.60s).

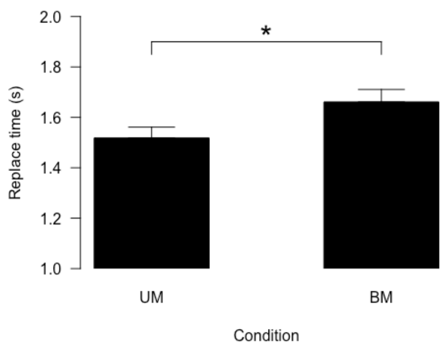


Figure 6.4: Mean replace time (± SE) for UM and BM conditions.

Release time

The initial ANOVA model for release time did not have normalised residuals, failing Shapiro-Wilk's test of normality ($p < 0.05$). Consequently, a log transformation of release time was used for difference testing. There was no main effect of group ($F(1, 38) = 1.12$, $p = 0.30$, $\eta2 = 0.03$; YA = 0.46s; OA = 0.54s), hand ($F(1, 38) = 0.10$, $p = 0.75$, $\eta2 = 0.00$; ND = 0.50s; D = 0.50s) or mass ($F(1, 38) = 3.78$, $p = 0.06$, $\eta2 = 0.09$; L = 0.49s; H = 0.52s), but there was a significant effect of condition ($F(1, 38) = 8.0$, $p = 0.007$, $\eta2 = 0.17$; UM = 0.48s; BM = 0.53s), with BM lifts generating an increased release time compared to UM lifts.

There was also an interaction present between group * hand ($F(1, 38) = 5.26$, $p = 0.027$, $\eta2 = 0.12$), data was collapsed across condition and mass to explore interaction. Post-hoc analysis exploring the group * hand interaction found no significant difference between YA and OA within ND hand ($p = 0.67$, $d = 0.14$) or D hand ($p = 0.07$, $d = 0.58$). Within group analysis revealed a significant difference between ND and D hands for YA ($p = 0.04$, $d = 0.50$) but not for OA ($p = 0.36$, $d = 0.21$). This interaction is displayed below in figure 6.5b.

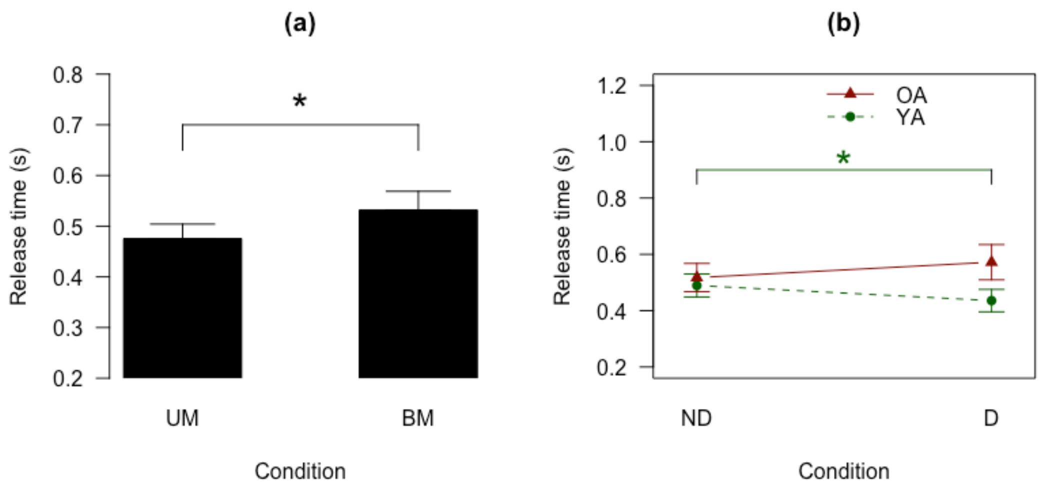


Figure 6.5: Mean release time (± SE) for (a) UM and BM and (b) YA and OA across ND and D hands, data collapsed across condition and mass.

Path length

A log transformation of path length was calculated for statistical analysis, as the raw data failed the assumption tests for equal variance. The results revealed a main effect of group ($F(1, 38) = 7.05$, $p = 0.01$, $\eta2 = 0.16$; YA = 21.8mm; OA = 18.0mm) with OA displaying a decreased path length. There was also a significant main effect of hand ($F(1, 38) = 17.5$, $p < 0.001$, $\eta2 = 0.32$; ND = 20.9mm; D = 19.0mm), with a decreased path length for the dominant hand, but no main effect of condition ($F(1, 38) = 0.1$, $p = 0.75$, $\eta2 = 0.00$; UM = 20.0mm; BM = 19.9mm) or mass ($F(1, 38) = 1.63$, $p < 0.21$, $\eta2 = 0.04$; L = 19.8mm; H = 20.1mm). No two, three or four-way statistically significant interactions (see appendix 9.3 table 9.6 for full details).

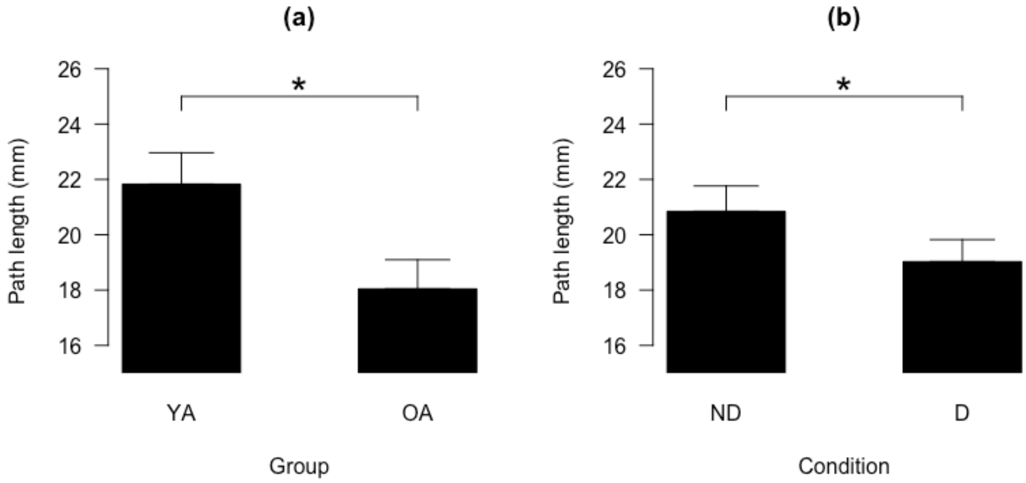


Figure 6.6: Mean path length (± SE) for (a) YA and OA (b) ND and D hands.

Hold height

No significant effects were found for group, condition, hand or mass for the height the object was held during the stable phase (see appendix 9.3 table 9.7 for full details).

Peak grip force

A log transformation of peak grip force was calculated and used for analysis, as the raw data failed assumption testing for equal variance. The ANOVA revealed a significant main effect of group ($F(1, 38) = 15.8$, $p < 0.001$, $\eta2 = 0.29$; YA = 7.9N; OA = 13.2N), condition ($F(1, 38) = 7.00$, $p = 0.01$, $\eta2 = 0.16$; UM = 10.4N; BM = 10.7N) and mass ($F(1, 38) = 206.2$, $p < 0.001$, $\eta2 = 0.84$; L = 8.4N; H = 12.7N), but no effects of hand ($F(1, 38) = 0.01$, $p = 0.93$, $\eta2 = 0.00$; ND = 10.5N, D = 10.6N). No further two, three or four-way interactions were present (see appendix 9.3 table 9.8 for full details). In summary, OA displayed an increase in peak GF compared to YA, bimanual conditions led to an increase in peak GF compared to unimanual conditions and heavy masses also led to an increase in peak GF compared to light masses (figure 6.7).

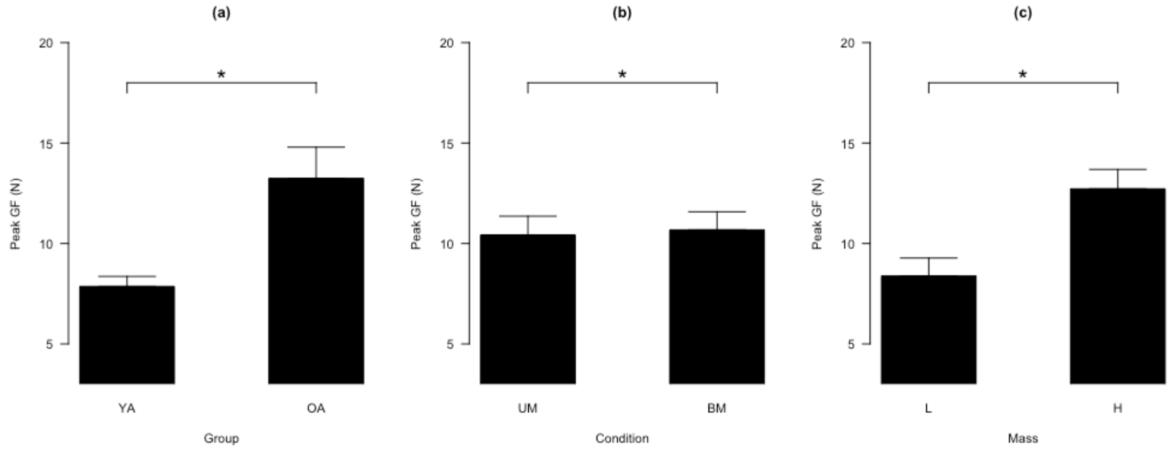


Figure 6.7: Mean peak GF (± SE) for (a) YA and OA groups (b) UM and BM conditions and (c) L and H masses.

Time to peak grip force

The initial ANOVA model for time to peak grip force did not have normalised residuals, failing Shapiro-Wilk's test of normality. Consequently, a log transformation of time to peak grip force data was calculated and used for statistical testing. The results revealed a significant main effect of condition ($F(1, 38) = 6.22$, p = 0.017, η2 = 0.14; UM = 1.0s; BM = 1.1s), with an increased time to peak GF during bimanual lifts, but there were no significant effects of mass ($F(1, 38) = 1.27$, p = 0.27, η2 = 0.03; L = 1.0s ; H = 1.1s), group ($F(1, 38) = 1.72$, p = 0.2, η2 = 0.04; YA = 1.0s; OA = 1.7s) or hand ($F(1, 38) = 2.71$, p = 0.19, η2 = 0.07; ND = 0.99s ; D = 1.1s). No two, three or four-way effects were present (see appendix 9.3 table 9.9 for full details).

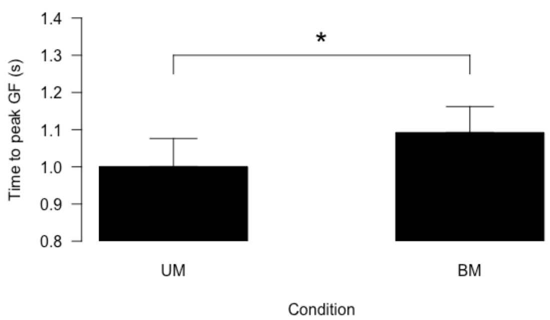


Figure 6.8: Mean time to peak GF (± SE) for UM and BM conditions.

Peak load force

Analysis of peak LF revealed a significant main effect of condition ($F(1, 38) = 4.79$, $p = 0.035$, $\eta 2 = 0.11$; UM = 3.59N; BM = 3.56N), with an increase peak LF during unimanual lifts. Also a main effect of mass ($F(1, 38) = 9737$, $p < 0.001$, $\eta 2 = 1.0$; L = 2.41N; H = 4.75N), with an increase LF for heavy masses, but no effect of group ($F(1, 38) = 0.70$, $p = 0.41$, $\eta 2 = 0.02$; YA = 3.61N; OA = 3.55N) or hand ($F(1, 38) = 0.38$, $p = 0.54$, $\eta 2 = 0.01$; ND = 3.59N; D = 3.56N). There were no two, three or four-way effects present (see appendix 9.3 table 9.10 for full details).

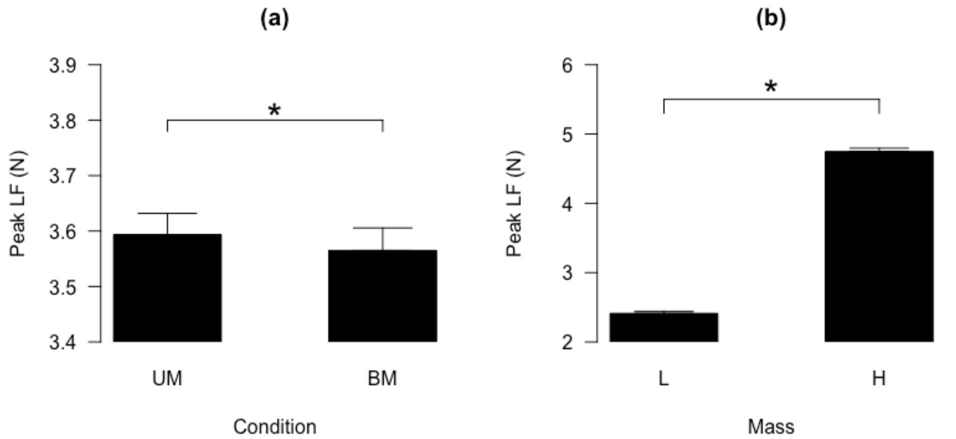


Figure 6.9: Mean peak LF (± SE) for (a) UM and BM conditions and (b) L and H masses. Please note figures (a) and (b) have different y-axis scales.

Time to peak load force

A log transformation of time peak load force was calculated as the raw data failed Levene's test for equal variance. The results revealed a significant effect of group ($F(1, 38) = 12.48$, $p = 0.001$, $\eta 2 = 0.25$; YA = 0.53s; OA = 0.76s), with OA taking longer to reach peak LF. There was also a main effect of condition ($F(1, 38) =136.3$, $p < 0.001$, $\eta 2 = 0.78$; UM = 0.56s; BM = 0.73s), with an increased time to peak LF during bimanual lifts, mass ($F(1, 38) = 78.7$, $p < 0.001$, $\eta 2 = 0.67$; L = 0.56s; H = 0.73s), with heavy objects showing an increased time to peak LF, but no effect of hand was present ($F(1, 38) = 0.46$, $p = 0.50$, $\eta 2 = 0.01$; ND = 0.64s; D = 0.65s). No two, three or four-way interactions were present (see appendix 9.3 table 9.11 for full details).

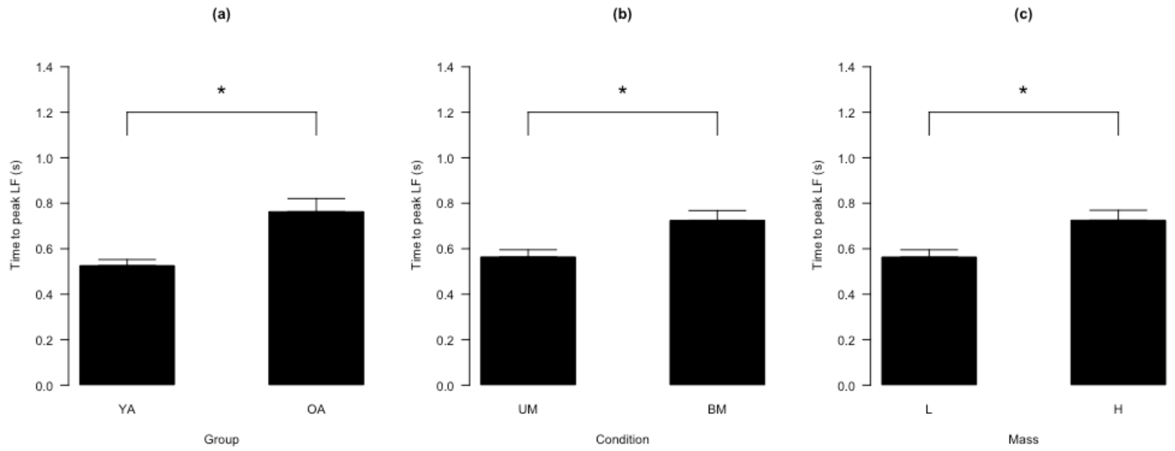


Figure 6.10: Mean time to peak LF (± SE) for (a) YA and OA groups (b) UM and BM conditions and (c) L and H masses.

Grip force to load force ratio at start of lift

A log transformation of grip force to load force ratio (GF:LF) was used for statistical testing, as the raw data failed Levene's test for equal variance. The results revealed a main effect of group ($F(1, 38) = 16.55$, $p < 0.001$, $\eta2 = .30$; YA = 2.21; OA = 3.93), mass ($F(1, 38) = 32.4$, $p < 0.001$, $\eta2 = .461$, L = 3.47; H = 2.67) and condition ($F(1, 38) = 4.46$, $p = 0.041$, $\eta2 = .105$; UM = 3.04; BM = 3.10), but no effect of hand ($F(1, 38) = 0.28$, $p = 0.60$, $\eta2 = 0.07$, ND = 3.02; D = 3.12). No two, three, or four-way interactions were present (see appendix 9.3 table 9.12 for full details). In summary, OA displayed an increase in GF:LF compared to YA, BM lifts result in an increased GF:LF compared to UM lifts, and GF:LF reduced when participants lifted the heavier mass (figure 6.11).

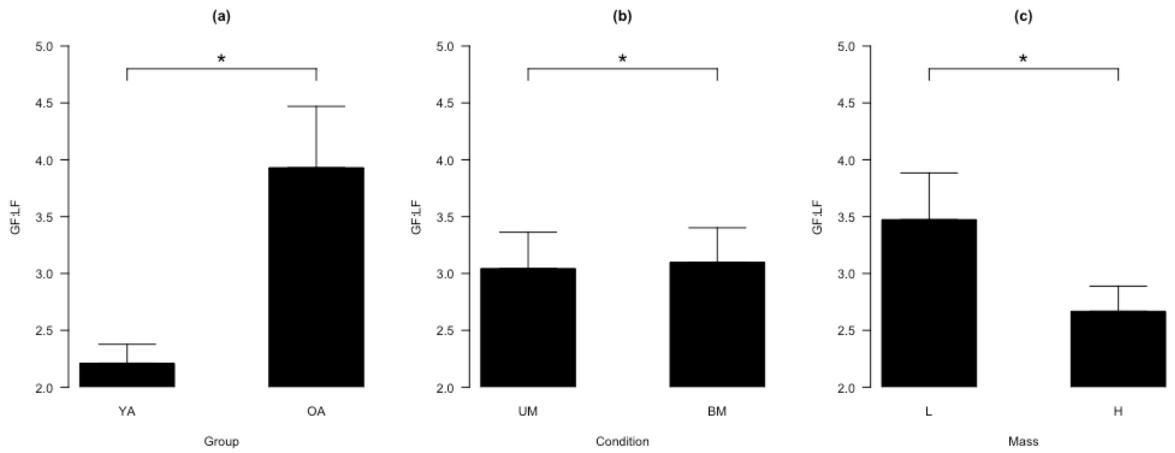


Figure 6.11: Mean GF:LF at start of lift (± SE) for (a) YA and OA groups (b) UM and BM conditions and (c) L and H masses.

Grip force to load force ratio during the stable phase

Raw data for GF:LF during the hold phase failed Levene's test for equal variance, therefore a log transformation of the data was calculated and used for testing. The testing revealed a main effect of group ($F(1, 38) = 16.31$, $p < 0.001$, $\eta 2 = .30$; YA = 1.85; OA = 3.11) with an increased GF:LF for OA, mass ($F(1, 38) = 37.1$, $p < 0.001$, $\eta 2 = .49$; L = 2.84; H = 2.15) with a decreased GF:LF for heavy objects and hand ($F(1, 38) = 4.72$, $p = 0.036$, $\eta 2 = .11$; ND = 2.37N, D = 2.60N), with an increased GF:LF for the dominant hand, but there was no effect of condition ($F(1, 38) = 1.15$, $p = 0.29$, $\eta 2 = .01$; UM = 2.47N, BM = 2.49N). There was a hand * mass interaction present ($F(1, 38) = 4.75$, $p = 0.04$, $\eta 2 = .21$), data was collapsed across group and condition to explore this interaction. Post-hoc analysis of hand * mass interaction found no significant change between hands when lifting heavy masses ($p = 0.18$, $d = 0.10$), but a significant difference between hands when lifting light masses ($p = 0.02$, $d = 0.21$) see figure 6.12b. As expected, there were significant differences within ND ($p < 0.001$, $d = 0.73$) and D ($p < 0.001$, $d = 0.74$) conditions when lifting light and heavy objects (figure 6.12b). No further two, three or four-way interactions were present (see appendix 9.3 table 9.13 for full details).

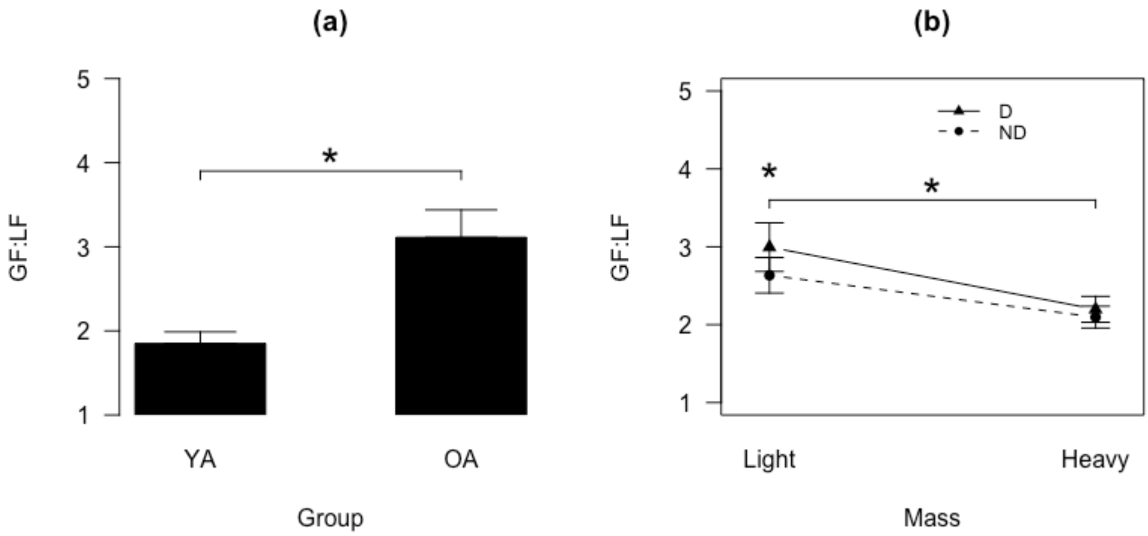


Figure 6.12: Mean GF:LF during the stable phase (± SE) for (a) YA and OA groups (b) ND and D hands across L and H masses.

Safety margin

Raw data for safety margin (SM) failed Levene's test for equal variance, therefore a log transformation of the data was used for statistical testing. The testing revealed a main effect of group ($F(1, 38) = 4.82$, $p = 0.034$, $\eta 2 = .11$; YA = 2.29N, OA = 5.26N), with an increase SM for OA, mass *(F(*1, 38) = 25.1, p <0.001, η2 = .40; L = 3.61N; H = 4.54N) with an increased SM for heavy objects and hand (*F*(1, 38) = 6.43, p = 0.015, η2 = .15, ND = 3.77N; D = 4.38N) showing an increased SM for the dominant hand. There was no effect of condition (*F*(1, 38) = 0.37, p = 0.55, η2 = .01, UM = 4.04N; BM = 4.11N) and no two, three or four-way interactions present. The results for group, hand and mass are shown below in figure 6.13.

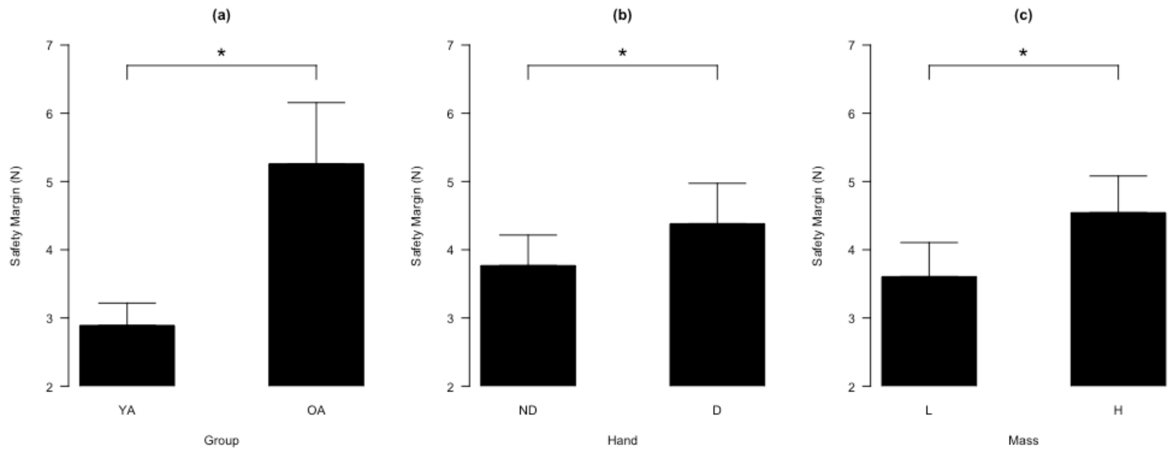


Figure 6.13: Mean safety margin (± SE) during the hold phase of the lift for (a) YA and OA (b) ND and D hands and (c) L and H masses.

Peak cross-correlation coefficient

Please see section 5.5.1 and figure 5.2 in chapter 5 for full details on how cross-correlation values were calculated. The ANOVA testing revealed a main effect of group (*F*(1, 38) = 5.46, p = 0.025, η2 = .13; YA = 0.68r; OA = 0.62r) with a decreased correlation coefficient for OA. There was also a main effect of mass (*F*(1, 38) = 23.83, p < 0.001, η2 = .39; L = 0.64r; H = 0.67r) with an increased correlation for heavy objects, but no effects of condition (*F*(1, 38) = 2.77, p = 0.10, η2 = .07; UM = 0.66r; BM = 0.65r) or hand (*F*(1, 38) = 2.68, p = 0.11, η2 = .07; ND = 0.66r; D = 0.65r). The results for group and mass are shown below in figure 6.14.

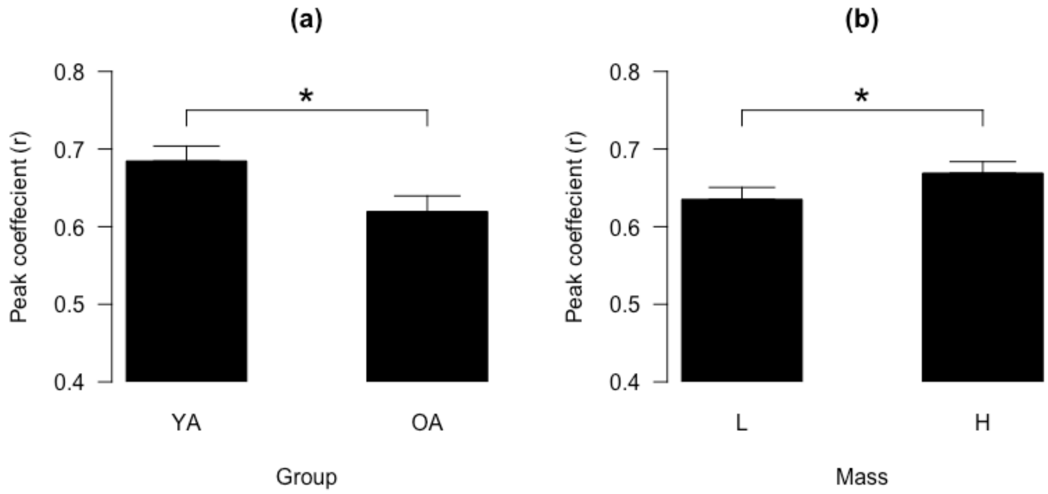


Figure 6.14: Mean peak cross-correlation coefficient (± SE) for (a) YA and OA (b) L and H masses.

Time-shift of peak cross-correlation

Analysis on the time-shift of the peak cross-correlation found a significant main effect of group ($F(1, 38) = 4.34$, p = 0.04, η2 = .10; YA = 9.0ms; OA = -2.8ms), with GF scaling ahead of LF for OA, but no effect of condition ($F(1, 38) = 0.12$, p = 0.74, η2 = .00; UM = 2.5ms; BM = 3.6ms), hand ($F(1, 38) = 0.00$, p = 1.0, η2 = .00; ND = 3.1ms; D = 3.1ms) or mass ($F(1, 38) = 0.30$, p = 0.59, η2 = .01; L = 4.5ms; H = 1.7ms). There was also a condition * hand interaction ($F(1, 38) = 6.14$, p = 0.02, η2 = .14) which was explored further with pairwise comparisons, after collapsing data across group and mass, but no test reached levels of significance ($p < 0.05$).

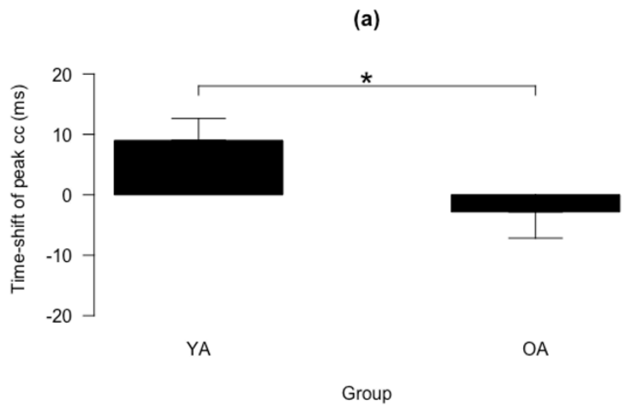


Figure 6.15: Mean time-shift of peak cross-correlation (± SE) for YA and OA. A negative value represents GF scaling before LF.

6.3.2 Biometric results

Analysis of Purdue Pegboard scores revealed a significant effect of group ($F(1, 38) = 11.1$, $p = 0.002$, $\eta 2 = 0.53$, YA = 13.0; OA = 11.0) with OA showing a decreased score. There was also a significant effect of hand ($F(2, 76) = 46.4$, $p < 0.001$, $\eta 2 = 0.55$, ND = 12.5; D = 13.1, BM = 10.6), but no group * hand interaction ($F(2, 76) = 0.60$, $p = 0.55$, $\eta 2 = 0.02$). Pairwise comparisons of hand found a significant difference between ND and BM conditions ($p < 0.001$, $d = 1.17$, ND = 12.5; BM = 10.6) and between D and BM conditions ($p < 0.001$, $d = 1.62$, D = 13.1, BM = 10.6) but not between ND and D conditions ($p = 0.16$, $d = 0.31$, ND = 12.5, D = 13.1). Figure 6.16 shows that, despite the mean difference between YA and OA groups in Purdue Pegboard score (table 6.1), there is considerable variance within both groups. Note that multiple participants in the OA group achieved manual dexterity scores in line with the YA cohort.

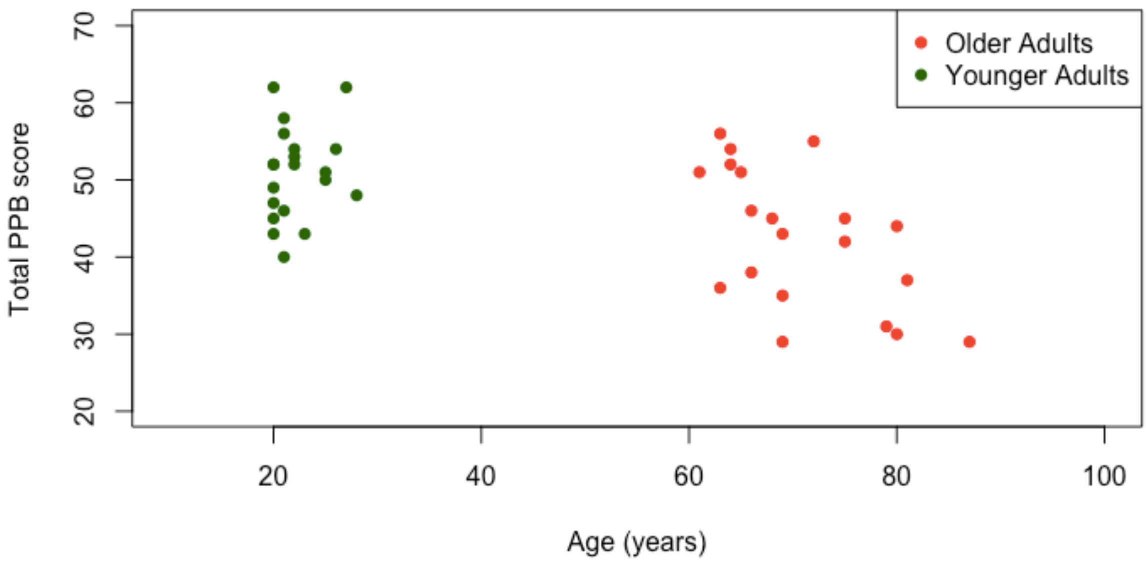


Figure 6.16: Total Purdue Pegboard score (sum of ND, D & BM) plotted against age for YA and OA.

Table 6.1: Biometric data (M ± SE) for YA and OA across both hands (D, ND). Notes: Semmes-Weinstein data presented is the total product of force required to elicit a response from all four testing sites on each hand. BM refers to the total score (ND and D hand) achieved during the bimanual phase of the Purdue Pegboard test.

	Younger Adults			Older Adults		
	ND	D	BM	ND	D	BM
Purdue Pegboard score (total pegs)	13.35 ± 1.7	14.00 ± 1.8	23.50 ± 3.22	11.55 ± 2.8	12.10 ±2.3	18.80 ± 4.7
Pinch force (kg)	7.91 ± 1.4	8.40 ± 1.3	-	8.32 ± 2.4	8.72 ± 2.5	-
Semmes-Weinstein total force (g)	0.13 ± 0.09	0.11 ± 0.02	-	0.27 ± 0.28	0.41 ± 0.38	-

The mixed ANOVA for maximum pinch force revealed a significant effect of hand ($F(1, 38) = 6.21$, p = 0.018, η2 = .14; ND = 8.12kg; D = 8.56kg) with an increased peak force for the dominant hand, but no significant effect of group ($F(1, 38) = 0.37$, p = 0.55; η2 = .09; YA = 8.16kg; OA = 8.52kg). Analysis of Semmes-Weinstein data found a significant effect of group ($F(1, 38) = 10.51$, p = 0.002; η2 = .46; YA = 0.12g; OA = 0.34g) with OA showing reduced tactile sensation, but no significant effect of hand ($F(1, 38) = 2.80$, p = 0.10, η2 = .07; ND = 0.20g, D = 0.26g). There was a group * hand interaction ($F(1, 38) = 4.44$, p = 0.042, η2 = .11) which was explored. Post-hoc analysis revealed significant differences between YA and OA within ND (p = 0.049, *d* = 0.66) and D (p = 0.003, *d* = 1.09) hands. No difference of hand was present within YA (p = 0.34, *d* = 0.22), or OA (p = 0.07, *d* = 0.43). Table 6.1 provides a summary of the biometric data for YA and OA.

6.3.3 EMG results

Dynamic lifting phase

The NMF analysis of the EMG data for YA and OA during the dynamic lifting phase returned an explained variance of 0.963 when compared to the original EMG dataset, indicating a strong representation of the original data (D'Avella et al., 2006). Figure 6.17 shows the invariant muscle weights that contribute to each synergy during the dynamic phase – from initial contact to the start of the stable phase.

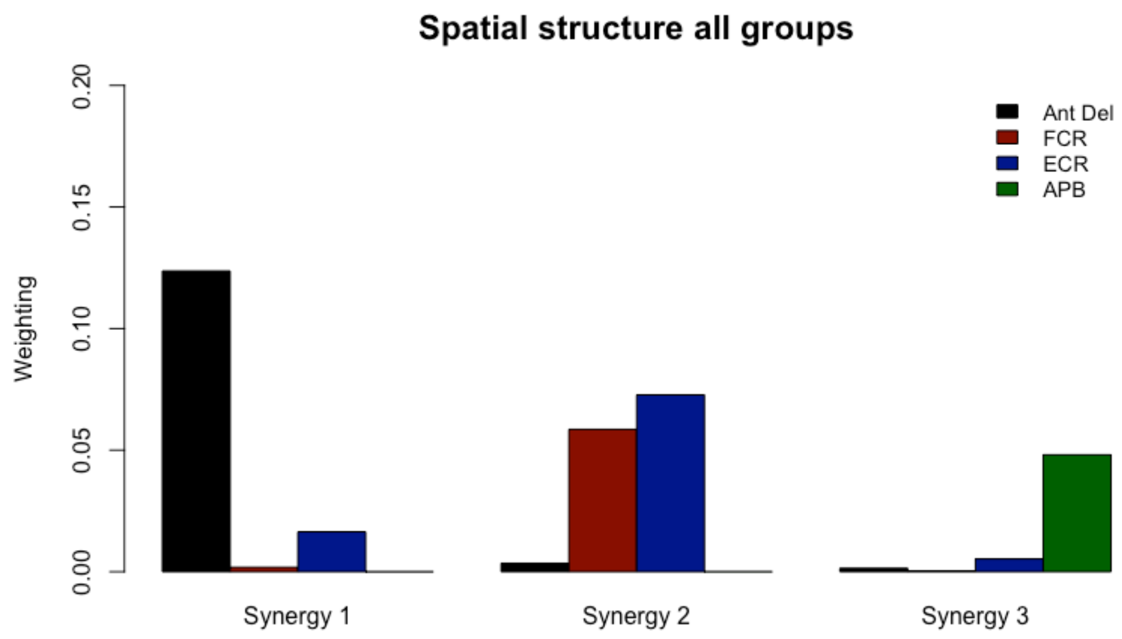


Figure 6.17: The invariant muscle weightings from the NMF ran on the dataset across all YA and OA data. The coloured bars represent the associated muscle component for each muscle synergy: Ant Del = Anterior Deltoid; FCR = Flexor Carpi Radialis; ECR = Extensor Carpi Radialis; APB = Abductor Pollicis Brevis.

Figure 6.18 shows the temporal weightings for muscle synergies one, two and three for YA and OA averaged across condition, hand and mass. This provides a visual guide for the statistical analysis that follows. Note the changes between synergies two and three for OA, compared to YA.

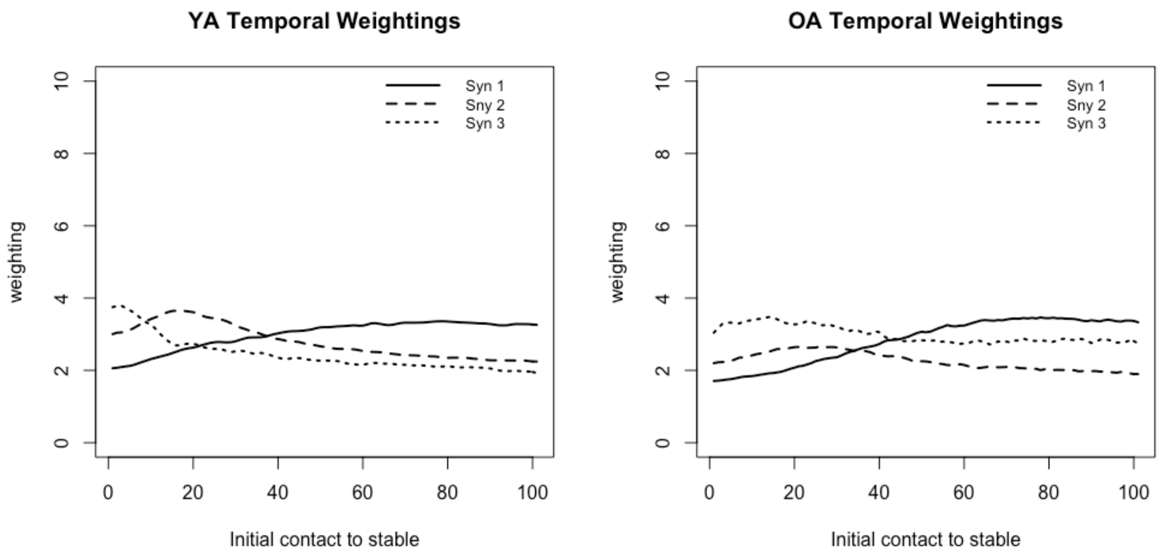


Figure 6.18: Mean temporal weightings for YA and OA from initial contact to the start of the stable phase (normalised to 101 datapoints).

Table 6.2 below shows the results for the Pearson's correlations ran between muscle synergies one, two and three for YA and OA to determine how independent or coupled each synergy's activation was in relation to one another. These values are averaged across condition, hand and mass. Table 6.2 shows an increased coupling between all muscle synergies in OA compared to YA.

Table 6.2: Mean (± SE) correlation coefficients between each muscle synergy for YA and OA groups during dynamic phase (contact to stable phase).

	Correlation 1 (S1 ~ S2)	Correlation 2 (S2 ~ S3)	Correlation 3 (S1 ~ S3)
YA	- 0.21 ± 0.17	0.13 ± 0.16	- 0.13 ± 0.16
OA	- 0.26 ± 0.24	0.23 ± 0.23	- 0.16 ± 0.28

The mixed-effects model ran on correlation one, assessing the temporal relationship between synergy one and synergy two found no significant effect of group ($F(1, 30) = 0.69$, p = 0.41; YA = - 0.21; OA = - 0.26), condition ($F(1, 173) = 1.58$, p = 0.21; UM = - 0.25; BM = - 0.22), hand ($F(1, 173) = 0.01$, p = 0.93; ND = - 0.23, D = - 0.23) or mass ($F(1, 173) = 1.02$, p = 0.31; L = - 0.25; H = - 0.22). There were no further two, three or four-way interactions ($p > 0.05$), see appendix 9.3 table 9.17 for full details.

Analysis of correlation two revealed a significant effect of group (*F*(1, 30) = 4.78, p = 0.04; YA = 0.13; OA = 0.23), but not of condition (*F*(1, 173) = 0.01, p = 0.91; UM = 0.19; BM = 0.19), hand (*F*(1, 173) = 0.00, p = 0.99; ND = 0.19, D = 0.19) or mass (*F*(1, 173) = 0.17, p = 0.68; L = 0.19, H = 0.18). There were no two, three or four-way interaction effects (see appendix 9.3 table 9.18 for full details).

The mixed-effects model ran on correlation three, assessing the temporal relationship between synergy one and synergy three found no significant effect of group (*F*(1, 30) = 0.05, p = 0.82; YA = - 0.13; OA = - 0.16), condition (*F*(1, 173) = 1.77, p = 0.18; UM = - 0.13; BM = - 0.16), hand (*F*(1, 173) = 2.28, p = 0.13; ND = - 0.17, D = - 0.13) or mass (*F*(1, 173) = 0.17, p = 0.68; L = - 0.15; H = - 0.14), but there was a significant group * mass interaction (*F*(1, 173) = 4.93, p = 0.028), data were collapsed across condition and hand to further explore this interaction. Post-hoc analysis found no significant group differences within L (p = 0.57, *d* = 0.20) or H (p = 0.30, *d* = 0.37) conditions and no differences were present within YA (p = 0.19, *d* = 0.34) or OA (p = 0.13, *d* = 0.40) between L and H masses. No further two, three or four-way interactions were present (see appendix 9.3 table 9.19 for full details).

Stable Phase

The NMF analysis run on the EMG data of YA and OA during the stable phase returned an explained variance of 0.962 compared to the original dataset. Figure 6.19 shows the invariant muscle weights that contribute to each synergy during the stable phase – from the start to the end of the stable phase.

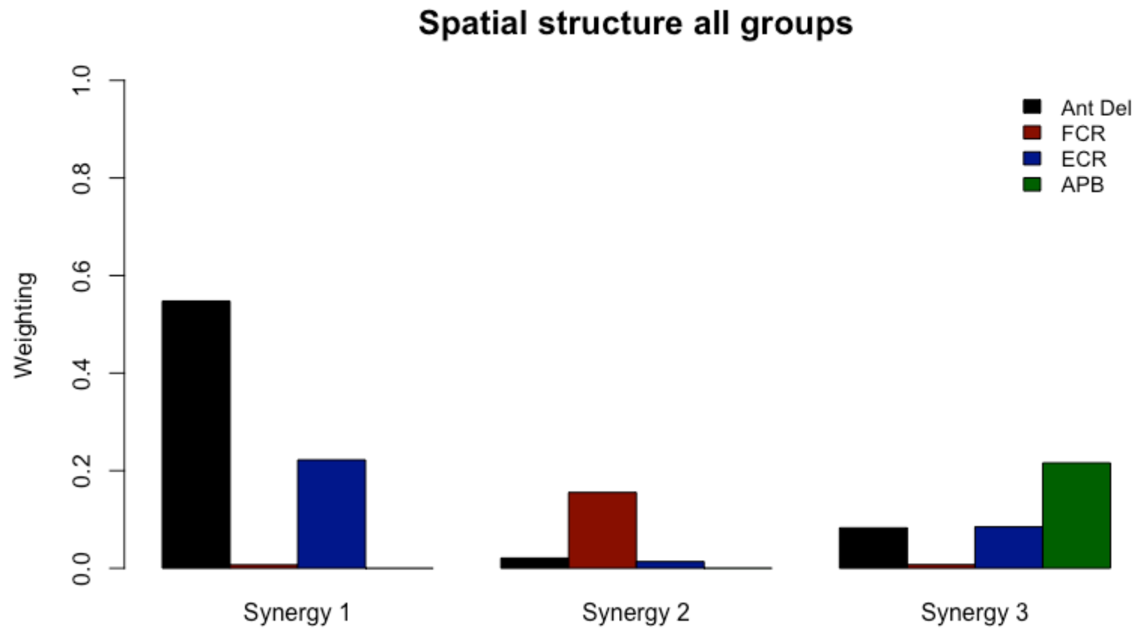


Figure 6.19: The invariant muscle weightings from the NMF ran on the dataset across all YA and OA during the stable phase. The coloured bars represent the associated muscle component for each muscle synergy: Ant Del = Anterior Deltoid; FCR = Flexor Carpi Radialis; ECR = Extensor Carpi Radialis; APB = Abductor Pollicis Brevis).

Figure 6.20 shows the temporal weightings for muscle synergies one, two and three, during the stable phase, for YA and OA averaged across conditions, hand and mass.

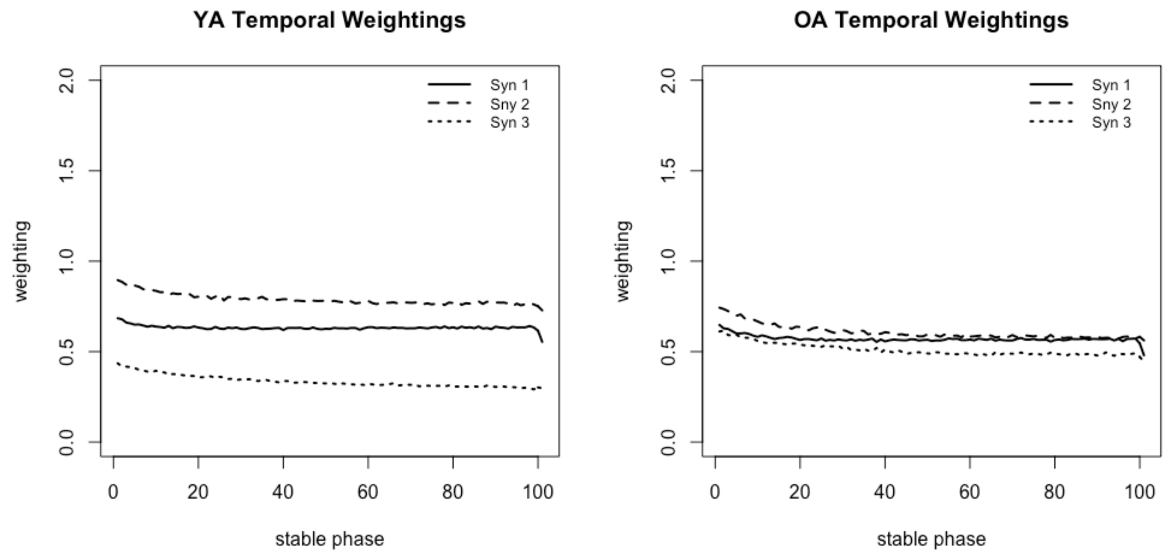


Figure 6.20: Mean temporal weightings for YA and OA from the start to end of stable phase (normalised over 101 datapoints).

Table 6.3 below shows the results for the Pearson's correlations ran between muscle synergies one, two and three for YA and OA during the stable phase. These values are averaged across condition, hand and mass.

Table 6.3: Mean (± SE) correlation coefficient between each muscle synergy for YA and OA groups during stable phase.

	Correlation 1 (S1 ~ S2)	Correlation 2 (S2 ~ S3)	Correlation 3 (S1 ~ S3)
YA	- 0.04 ± 0.11	0.11 ± 0.18	- 0.21 ± 0.17
OA	- 0.05 ± 0.13	0.09 ± 0.19	- 0.24 ± 0.21

The mixed-effects model ran on correlation one, assessing the temporal relationship between synergy 1 and synergy 2 during the stable phase found no significant effect of group ($F(1,30) = 0.00$, p = 0.97; YA = - 0.04; OA = - 0.05), condition ($F(1, 173) = 0.39$, p = 0.53; UM = - 0.04; BM = - 0.05), hand ($F(1, 173) = 0.06$, p = 0.81; ND = - 0.04, D = - 0.05) or mass ($F(1, 173) = 0.64$, p = 0.42; L = - 0.04; H = - 0.05). There were no two, three or four-way interactions present (see appendix 9.3 table 9.20 for full details). Analysis on correlation two also revealed no significant effect of group ($F(1, 30) = 0.31$, p = 0.58; YA = 0.11; OA = 0.09), condition ($F(1, 173) = 0.96$, p = 0.33; UM = 0.11; BM = 0.09), hand ($F(1, 173) = 1.93$, p = 0.17; ND = 0.11, D = 0.08) or mass ($F(1, 173) = 1.21$, p = 0.27; L = 0.11, H = 0.09). Again, no two, three or four-way interactions were present (see appendix 9.3 table 9.21 for full details).

Analysis on correlation three found no significant effect of group ($F(1, 30) = 1.04$, p = 0.32; YA = - 0.21; OA = - 0.24) or mass ($F(1, 173) = 1.47$, p = 0.23; L = - 0.21, H = - 0.24), but significant effects of hand ($F(1, 173) = 9.83$, p = 0.002; ND = - 0.19, D = - 0.25) and condition ($F(1, 173) = 4.58$, p = 0.03; UM = - 0.20; BM = - 0.25). There was also a group * mass interaction ($F(1, 173) = 6.74$, p = 0.01) and group * hand interaction ($F(1, 173) = 10.58$, p = 0.001). Data were collapsed across factors to explore the interactions. Post-hoc analysis of the group * hand interaction revealed significant difference between groups within the D hand (p = 0.01, d = 1.00), but no differences within ND hand (p = 0.84, d = 0.08). YA showed no differences between hands (p = 0.93, d = 0.03), whereas there was a difference of hand within OA (p = 0.03, d = 0.83). Post-hoc analysis of group * mass showed a similar pattern, with no group differences present in L (p = 0.47, d = 0.26), but a difference within H masses (p = 0.04, *d* = 0.75). No difference of mass was present with YA (p = 0.12, *d* = 0.41), but there was a significant difference between L and H masses for OA (p = 0.001, *d* = 0.99).

6.4 Discussion

The first aim of this study was to explore kinematic, kinetic and muscle synergy changes between YA and OA across anticipatory and reactive stages of grasping. The second aim was to assess kinematic, kinetic and muscle synergy changes across unimanual and bimanual tasks performed by YA and OA. Finally, manual dexterity, pinch strength and cutaneous sensitivity data were collected to quantify biometric differences between YA and OA. In short, the results show OA i) take longer to grasp objects before they begin the transport phase, ii) use an increased GF:LF during anticipatory and reactive stages of lifting and iii) show a reduced ability to scale GF to LF during anticipatory stages of lifting. The results highlight changes in OA during anticipatory and reactive phases of grasping. Both YA and OA show consistent changes as they transition from UM to BM conditions suggesting bimanual grasping mechanisms are preserved in OA. Finally, OA show reduced manual dexterity and cutaneous sensitivity when compared to YA, but no changes in pinch strength. The following sections discuss these findings in more detail.

6.4.1 Older adults show slowing in unimanual and bimanual grasping

Previous research has reported OA perform upper limb tasks more slowly than YA, particularly when tasks become more complex (Smith et al., 1999). Findings from this study support this notion, with OA taking longer to execute the pre-loading and loading phase compared to YA (figure 6.2a). During this phase participants are required to securely place their finger(s) and thumb in contact with the object, in a way that minimises un-wanted torque (Holt et al., 2013; Endo et al., 2009). Un-wanted torque is defined as forces acting laterally to grip force that causes the object to rotate and potentially slip from a persons' grasp. Findings from this experiment indicate that OA take more time to place their fingertips, before applying an upward, load force. The increased loading time observed in this experiment may reflect OA refining their digit placement to minimise un-wanted torque for the up-coming lift, as previous research has reported – OA are less able to accurately place their digits on contact points and produce more unwanted torque during grasping tasks (Parikh and Cole, 2012).

This study was able to extend the slowing of movements hypothesis to bimanual grasping. The group difference in bimanual lifts between YA and OA are similar to those seen in unimanual trials, indicating both groups showed similar levels of slowing as they transitioned to bimanual tasks. Bimanual tasks are considered to be more complex (Endo et al., 2009), as both hands must be temporally and spatially orchestrated. Considering the pre-loading and loading phases require accurate placement of digits to minimise torque for the up-coming lift (Wing and Lederman, 2009), it makes sense that both groups show an increase in loading time for bimanual lifts. However, previous research has revealed an exaggerated slowing for OA during more complex unimanual tasks (Smith et al., 1999). Such exaggerated slowing was not present in the current study, when moving from unimanual to bimanual tasks, potentially indicating OA are more able to cope with unimanual to bimanual increases in task complexity, rather than increased complexity within a unimanual setting. Both groups showed a lower peak load force, increased peak grip force and increased GF:LF when lifting with both hands, suggesting a slower, more cautious lifting strategy for bimanual lifts is present in both YA and OA.

6.4.2 Kinetic changes in older adults' grasping

A commonly reported finding is that OA exhibit higher levels of grip force compared to YA (Cole, 1991; Cole, 2009; Lowe, 2001). There are various ways of calculating this metric, with the extraction of the peak grip force during the trial being the most common approach (Cole, 1991; Gilles and Wing, 2003). However, the mean GF:LF taken over a set timeframe of the lift offers a more robust measure of heightened grip force compared to one discrete data point, such as peak grip force (Lowe, 2001). To compare these approaches this study assessed i) peak GF, ii) GF:LF during the start of the lift and iii) GF:LF during the stable phase. Irrespective of measure, OA showed an increase in GF – indicating OA show significantly higher GF during anticipatory and reactive phases of the lift, across unimanual and bimanual conditions. Both YA and OA showed a decreased in GF:LF as they lifted the heavier mass, evident during the start of the lift and during the stable phase. This may seem counterintuitive, but previous research has indicated humans preserve a consistent safety margin when lifting objects of differing mass, rather than using a consistent GF:LF (Johansson and Westling, 1984; Hadjiosif and Smith, 2015). For example, when a light object is lifted with a GF of 5N, the object may begin to slip when GF reduces to 3N, leaving a safety margin of 2N (5N - 3N). When switching to an object double the mass GF may only scale to 8N, with the object beginning to slip at 6N – preserving a safety margin of 2N. This is an example where GF:LF does not stay constant when switching to heavier mass; instead safety margin of 2N is preserved.

This study provides evidence that OA show increased grip forces during grasping regardless of changing task constraints – across both hands, differing masses and unimanual and bimanual conditions, however the underlying cause for increased grip force in OA is still unresolved. For example, it has been noted that OA exhibit more slippery skin and a lower coefficient of friction when grasping objects (Diermayr et al., 2011). In contrast, other researchers (Cole, 1991), have suggested the increased grip force and safety margin is no more than a learned strategy to prevent the objected being dropped. A third hypothesis is that the increased grip force is used to mitigate reduced anticipatory control, but there has been mixed findings to support this concept – a previous review of literature concluded that anticipatory control is "marginally, if at all impaired in the elderly" (Diermayr et al., 2011, pg 223). However, as stated in the introduction of this chapter, this conclusion is based on limited analysis techniques that have been used in ageing research to date. A cross-correlation analysis assessing the relationship between changes in grip force (ΔGF) and changes in load force (ΔLF) has proved useful in detecting reduced anticipatory control in clinical populations (Duque et al., 2003; McDonnell et al., 2006), but had not been used in ageing grasp-lift-replace studies. Data from this experiment show OA have a significantly reduced ability to scale changes in GF to changes in LF during the transport phase (figure 6.14a) indicating reduced anticipatory control. This finding was consistent across both hands, unimanual and bimanual conditions and changes to the object mass. OA also scaled GF slightly in advance of LF and, on average, 12ms earlier than YA (figure 6.15). The reduced peak correlation coefficient and altered time-shift observed in OA aligns with the findings in clinical populations suffering with sensorimotor loss (Duque et al., 2003; McDonnell et al., 2006). By scaling GF before the anticipated change in load force, OA give themselves a wider temporal window for error.

6.4.3 Muscle synergy changes in older adults' grasping

The movements and forces required to successfully grasp, and lift objects are a product of highly complex sequences of muscular contractions applying force to the skeleton. Previous studies assessing muscular control have proposed the CNS simplifies the problem of individually controlling muscles, by sub-grouping muscle into synergist groups (Bizzi et al., 1991; Delis et al., 2013). Muscle synergies comprise of coordinated activations of groups of muscles, with time-varying profiles (D'Avella et al., 2006). From this perspective, control of movement is simplified as the CNS has to control far fewer parameters to manage across the movement cycle. The NMF analysis in this study assessed how a simple muscular model of the upper arm (Ant Del, FCR, ECR and APB) could be broken down into three invariant, synergistic muscle groups for the grasping and lifting task (figures 6.17 & 6.19), with time-varying profiles (figures 6.18 & 6.20). The muscle groupings formulated from the NMF analysis indicate the FCR and ECR were well coordinated throughout the dynamic phase whereas the Ant Del and APB were activated independently (figure 6.17). These findings support the pre-determined functions of these muscles during grasping tasks to i) flex the shoulder, ii) stabilise the wrist joint and iii) control grip force (Maier and Hepp-Reymond, 1995; Lemon et al., 1995; Holmes et al., 2015). Subsequent correlation analysis between time-varying profiles (MS1, MS2 and MS3) provides a novel insight into how these muscle synergies were coordinated in YA and OA.

Correlations performed on time-varying profiles of these muscle synergies show that OA exhibit a significant increase in temporal coupling between MS2 and MS3 across the dynamic lifting phase (table 6.2). YA selectivity de-couple APB activation from FCR and ECR activation, particularly during the first 40% of the dynamic phase (figure 6.18), whereas OA show higher levels of symmetry between the temporal profiles of synergies two and three across the entire dynamic phase (figure 6.18). This increased muscle synergy coupling present in OA may explain the kinetic and kinematic changes observed between YA and OA during the anticipatory phase of grasping. Previous research in EMG and ageing has found OA show increased levels of muscle activation during walking tasks and greater co-contraction between antagonistic muscle pairs during lower-limb maximum force production tasks (Macaluso et al., 2002). To date, there has been limited research assessing changes in muscle recruitment patterns for OA performing functional, upper limb tasks. Findings from this experiment extend the work of Macaluso et al. (2002) showing OA also display a reduced ability to independently recruit muscles outside antagonistic pairs. The increased coactivations observed in OA offer the motor system less affordances to adapt and attune to dynamic task constraints (Turvey, 1990). For example, the changing GF and LF rates during the loading and transport phases during grasping (Johansson and Westling, 1984). These changes in muscle synergies during the dynamic phase may explain why OA are less able to adapt GF values to changes in LF during the initial stages of lifting (figure 6.14a). Controlling the dynamic relationship between GF and LF is deemed a critical attribute of successful grasping (Johansson and Westling, 1984; Duque et al., 2003; Grover et al., 2019) and may help explain why OA show a reduced capacity to grasping and manipulate objects during ADL.

6.4.4 Biometric changes in older adults

Statistical testing revealed OA, on average, show a decrease in manual dexterity, cutaneous sensitivity, but not in pinch strength. Not seeing a decline in pinch strength within the OA group was unexpected, as previous research has documented declines in maximum power grip within OA (Martin et al., 2015) and reduced levels of muscle mass (Carmeli et al., 2003a). OA significant reduction in manual dexterity and cutaneous sensitivity provides strong evidence, that as a population, OA exhibit a loss in sensorimotor function (Martin et al., 2015; Desrosiers et al., 1999). Although, with closer inspection of the OA data we can see that not all OA demonstrate diminished sensorimotor function when compared to YA (figure 6.16). Consequently, group differences between YA and OA may not fully portray age-related motor decline – as some OA do not exhibit a decline in motor function, based on Purdue Pegboard data from this experiment (figure 6.16). Thus, future research wishing to better understand age-related motor decline should use tests such as the Purdue Pegboard and/or Semmes-Weinstein test to stratify OA into functional groups.

6.5 Conclusion

This experiment provides further evidence of differences in grasping between YA and OA. OA show an increased loading time, increased GF:LF ratio during the initial lifting stages and during the stable phase which results in an increased safety margin when holding objects. The decreased cross-correlation coefficient between ΔGF and ΔLF indicates OA exhibit inhibited anticipatory control during grasping. This reduced anticipatory control may contribute to the slower lifting strategy and increased safety margin we observe during grasping tasks. EMG data reveals OA show greater co-activation between forearm (FCR and ECR) and hand (APB) muscles during the initial stages of lifting and grasping. OA inability to selectively recruit distal muscle synergies may explain the kinetic and kinematic grasping changes observed between

YA and OA, and their reduced capacity to scale grip force to changes in load force. These finding are consistent across unimanual and bimanual conditions and changes in object mass. Biometric data indicates not all OA display reduced sensorimotor function compared to YA. With this in mind, future research should consider using functional tests, alongside chronological age to study age-related motor decline.

Chapter 7 – Grasping Characteristics in Older Adults with Good & Poor Levels of Manual Dexterity

7.1 Introduction

Experiment two (chapter 6) revealed kinematic, kinetic and muscle activation differences in grasping between younger adults (YA) and older adults (OA). One might conclude that the ageing process itself underlies these group differences, and hence chronological age can be used to explain motor decline as a function of age. However, Perdue Pegboard data indicated a high degree of heterogeneity in manual dexterity scores within the OA sample, with many OA in their 60's and 70's performing just as well as YA in manual dexterity tests (chapter 6, figure 6.16). Previous research has shown that, despite the general trend of manual dexterity reducing as a consequence of age, individuals in their 60's, 70's and 80's show wide-ranging manual dexterity capabilities (Desrosiers et al., 1999). Consequently, results from experiment two (chapter 6) cannot fully explain age-related decline in motor function – as Purdue Pegboard data suggests the OA group contains individuals with high and low manual dexterity capabilities. Grasping paradigms offer great insight into the anticipatory and reactive mechanisms used by individuals to grasp and manipulate objects (Cole, 1991; Gilles and Wing, 2003; Parikh and Cole, 2012), but to ensure the findings explain age-related decline in motor function the samples selected need to be stratified based age and functional tests measuring manual dexterity. This approach would allow a comparison of anticipatory and reactive grasping mechanisms present in dextrous OA and OA showing age-related decline in manual dexterity.

Manual dexterity is defined as "the ability to use one's hands' or the ability to manipulate objects with the hands" (Desrosiers et al., 1995, pp 217). Manual dexterity can be further broken down into fine dexterity – referring to one's ability to manipulate objects with the distal parts of the fingers, and gross dexterity – less refined movements of the hand and fingers. Tasks of daily living require both gross and fine aspects of dexterity, such as the control required to dress oneself and manipulate objects for cooking and eating. The Purdue Pegboard test offers one solution for measuring manual dexterity, that requires gross hand movements and elements of fine dexterity (Desrosiers et al., 1995). Despite the test's origin dating back to the 1940's, the Purdue Pegboard test is still the most widely used today for assessing hand function during therapy, rehabilitation and for research purposes (Gonzalez et al., 2017). Previous research has shown the Purdue Pegboard test can detect mean differences between age groups of OA (in their 60s, 70s and 80s), whilst still being able to appreciate the range of manual dexterity abilities that exists within each age-range (Desrosiers et al., 1995). The combination of factors above makes the Purdue Pegboard a useful tool for separating OA with good and poor manual dexterity.

Based on this rationale, experiment three will use the Perdue Pegboard to cluster OA into two subgroups – OA with 'good' and 'poor' levels of manual dexterity. Subsequent analysis will examine the anticipatory and reactive mechanisms that are present in these subgroups to better understand the differences between healthy ageing and age-related decline in manual dexterity. The research aims of this study are: i) To determine which grasping variables (kinetic, kinematic and muscle synergy coupling) distinguish OA with good manual dexterity, from those with poor levels of manual dexterity. ii) To establish whether OA with good levels of manual dexterity show similar grasping strategies to YA, or whether they show emergent strategies as a result of healthy ageing.

7.2 Methods

7.2.1 Participants

Previous research has reported age-related decline in motor function after the age of 50 years old (Coats et al., 2014). Therefore, the inclusion criteria for older adults in this experiment was reduced from 60 to 50 years old to include a wider range of potential manual dexterity levels. An additional 15 OA were recruited and added to the data collected in experiment two (chapter 6). The group of YA consisted of 20 healthy adults (M = 22.2 ± 2.59yrs old; Female = 14). The group of OA consisted of 35 healthy adults (M = 70.74 ± 7.76yrs old; Female = 22). There were three left-handed participants in the YA group and six left-handed participants in the OA group, identified by the asking participants which was their preferred hand for performing activities of daily living (ADL).

7.2.2 Procedure

All participants took part in the grasping and lifting tasks, involving both hands, two mass conditions and unimanual and bimanual components (see the chapter 5, section 5.5.1 for full details). This was followed by a set of slip-tests and collection of biometric data: max pinch strength, Semmes-Weinstein monofilament test and Purdue Pegboard test. See the chapter 5 section 5.5.3 for full details of the biometric testing procedures.

7.2.3 Data analyses

All data analyses for experiment three were performed in R Studios (v 1.1.463). Cluster analysis was performed on the total Purdue Pegboard scores of the OA group to sub-divide the OA into two sub-groups: 1) OA Good – with higher scores of manual dexterity, and 2) OA Poor – older adults with lower scores of manual dexterity. A k-means approach was used to perform the cluster analysis aiming to minimise the within sum of squares of Purdue Pegboard scores within the two new groups, measuring the Euclidian distance between points (Hartigan and Wong, 1979). The analysis was performed using the R package factoextra (Kassambara & Mundt 2017).

Grasping variables

Once the cluster analyses had been completed, grasping data from the three groups (YA, OA Good, OA Poor) was visually inspected using line plots (mean ± standard error) across within-subjects factors (Condition, Hand and Mass). Boxplots were also used to assess the spread of the data and identify outliers that might skew the model fitting process. Mixed effects linear models were used to assess group and within-subjects factor differences in the grasping task. The models were structured to have a between-subjects fixed effect of group (YA, OA Good, OA Poor) and three within-subjects fixed effects: 1) Condition, with two levels: unimanual (UM) and bimanual (BM). 2) Hand, containing two levels: non-dominant (ND) and dominant (D) and 3) Mass, with two levels: light (L) and heavy (H). All models contained participants as a random effect, nested within group, condition, hand and mass. This approach best fitted the data but did limit the ability to quantify effect sizes for the main effects and interactions during the subsequent ANOVA analysis (Zuur et al., 2009; Harrison et al., 2018).

Where appropriate, the data were log-transformed to normalise the model's residuals. Due to the limited number of data points in the OA Poor group, all models were limited to having random intercepts, with no random slopes. The rationale being to reduce over-fitting the model to the dataset (Harrison et al., 2018). Fifteen of the 16 variables from experiment two were analysed. Time to peak load force was removed from testing, as findings from experiment two indicated time to peak load force is a direct function of loading time (see appendix 9.4). The nlme package in R was used to perform all analysis (Pinheiro et al., 2019), once the models were built and tested, the ANOVA function was used to test between and within factor differences. One-way ANOVAs and Welch's t-tests were used for post-hoc tests between groups and interactions (Ruxton, 2006; Derrick and White, 2016).

EMG variables

Mixed effects linear models were used to test statistical significance of correlations ran on the temporal weightings of the NMF outputs (see chapter 5, section 5.2.2 for full details of the NMF analysis). Mixed effects linear models were used to test between groups and across conditions as they are more robust to dataset with missing values (Zuur et al., 2010), caused by data removed due to EMG artefacts (see section 5.5.2). The models were structured to have a between-subjects fixed effect of group (YA, OA G and OA P) and three within-subjects fixed effects: 1) Condition, with two levels: unimanual (UM) and bimanual (BM). 2) Hand, containing two levels: non-dominant (ND) and dominant (D) and 3) Mass, with two levels: light (L) and heavy (H). All models contained participants as a random effect, nested within group, condition, hand and mass (Zuur et al., 2009; Harrison et al., 2018). The nlme package in R was used to perform all analysis (Pinheiro et al., 2020), with the ANOVA function used to extract between and within factor differences. One-way ANOVA's and Welch's t-tests were used for post-hoc tests between groups and conditions.

Biometric variables

Maximum pinch force and Semmes-Weinstein data were analysed using two separate mixed ANOVA's, with group (YA, OA G and OA P) as a between-subjects factor and hand (ND and D) as a within-subjects factor. A mixed ANOVA was also performed on Purdue Pegboard scores, as structured above, however the between-subjects factor had three levels: D, ND and aggregated BM scores. Welch's t-tests were used for post-hoc testing biometric data between groups and hand.

7.3 Results

7.3.1 Cluster analysis

Manual dexterity scores for all 35 participants over the age of 50 were put into the cluster analysis. The within sum of squares reduced from 2013.9 with one cluster to 750.3 with two clusters (mean scores: OA G = 47.1, OA P = 34.2), indicating the two newer groups better represented the variance in manual dexterity for OA. The resulting OA groups used for further analysis are displayed below in figure 7.1.

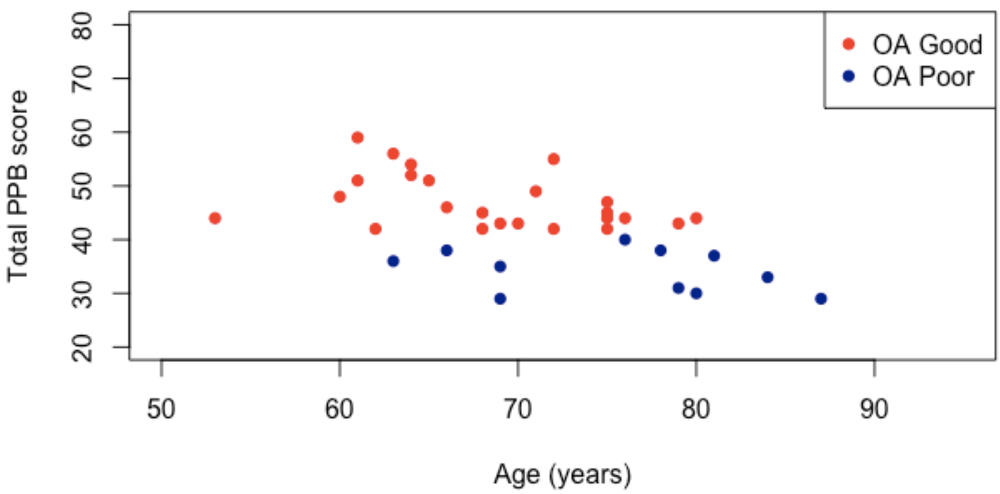


Figure 7.1: Age and total Purdue Pegboard scores for the two sub-groups following the cluster analysis.

7.3.2 Grasping & lifting analysis

Loading time

Statistical analysis of loading time indicated a significant main effect of group ($F(2, 52) = 7.94$, $p = 0.001$), condition ($F(1, 364) = 154.6$, $p < 0.001$, UM = 0.49s; BM = 0.68s), mass ($F(1, 364) = 91.55$, $p < 0.001$, L = 0.50s; H = 0.67s) but not of hand ($F(1, 364) = 0.11$, $p = 0.74$, ND = 0.59s; D = 0.59s). Pairwise comparisons of group showed YA (mean = 0.41s) use a shorter loading time compared to OA G (mean = 0.70s) ($p = 0.001$, $d = 1.24$) and OA P (mean = 0.66s) ($p = 0.02$, $d = 1.21$), but no differences were present between OA G and OA P ($p = 1.00$, $d =$

0.10). Figure 7.2 displays the key findings of (a) group differences between YA and both OA groups, (b) bimanual lifts leading to an increased loading time and (c) heavier masses leading to a longer loading time. There were no two, three or four-way interactions present (see appendix 9.5 table 9.23 for further details).

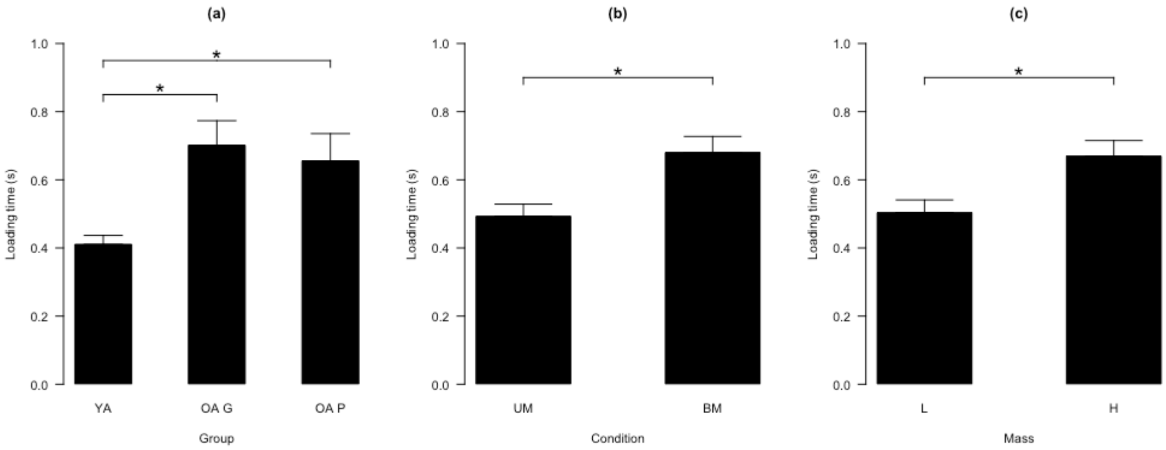


Figure 7.2: Mean loading time (± SE) for (a) YA, OA Good and OA Poor (b) UM and BM conditions and (c) L and H masses.

Transport time

Analysis of transport time revealed no significant main effect of group ($F(2, 52) = 0.02$, $p = 0.98$, YA = 1.29s; OA G = 1.29s; OA P = 1.29s), condition ($F(1, 364) = 3.53$, $p = 0.06$, UM = 1.27s; BM = 1.30s), hand ($F(1, 364) = 0.90$, $p = 0.34$, ND = 1.29s; D = 1.28s), or mass ($F(1, 364) = 0.14$, $p = 0.71$, L = 1.29s; H = 1.29s). Testing did reveal a significant condition * hand * mass * group interaction ($F(2, 364) = 4.03$, $p = 0.019$), however no significant two or three-way interactions were found (see appendix 9.5 table 9.24 for further details).

Stable time

Analysis of stable time showed no significant main effect of group ($F(2, 52) = 1.70$, $p = 0.19$, YA = 9.93s; OA G = 9.53s; OA P = 9.64s), hand ($F(1, 364) = 0.43$, $p = 0.51$, ND = 9.69s; D = 9.70s), or mass ($F(1, 364) = 0.28$, $p = 0.60$, L = 9.71s; H = 9.68s), but a significant main effect of condition ($F(1, 364) = 11.59$, $p < 0.001$, UM = 9.80s; BM = 9.60s), with a slight decrease in stable time for BM conditions (figure 7.3). No further two, three or four-way effects were found.

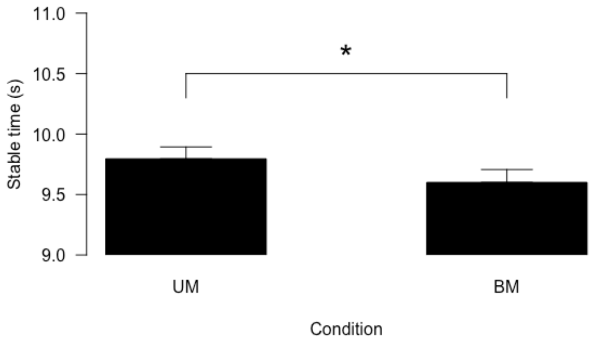


Figure 7.3: Mean stable time (± SE) for UM and BM conditions.

Replace time

Analysis of replace time found no significant main effect of group ($F(2, 52) = 1.33$, $p = 0.27$; YA = 1.59s; OA G = 1.47s; OA P = 1.61s), hand ($F(1, 364) = 0.52$, $p = 0.47$, ND = 1.54s; D = 1.55s), or mass ($F(1, 364) = 3.52$, $p = 0.061$, L = 1.52s; H = 1.56s), but a significant main effect of condition ($F(1, 364) = 66.9$, $p < 0.001$, UM = 1.47s; BM = 1.61s), with an increased replace time for BM conditions (figure 7.4). No further two, three or four-way interactions were present.

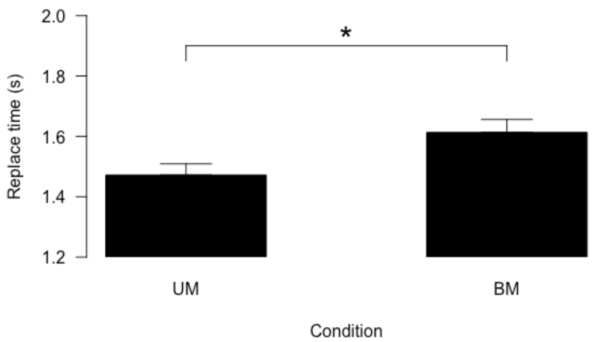


Figure 7.4: Mean replace time (± SE) for UM and BM conditions.

Release time

A log transformation of release time was used for all analysis, as the raw data resulted in non-normally distributed residuals. The analysis revealed no significant effect of group ($F(2, 52) = 1.00$, $p = 0.37$; YA = 0.46s; OA G = 0.55s; OA P = 0.51s), hand ($F(1, 364) = 1.61$, $p = 0.21$, ND = 0.52s; D = 0.50s), or mass ($F(1, 364) = 1.64$, $p = 0.20$; L = 0.50s; H = 0.52s), but there was a significant effect of condition ($F(1, 364) = 23.1$, $p < 0.001$, UM = 0.47s; BM = 0.55s) with an increased release time for bimanual conditions. No further two, three or four-way effects were present.

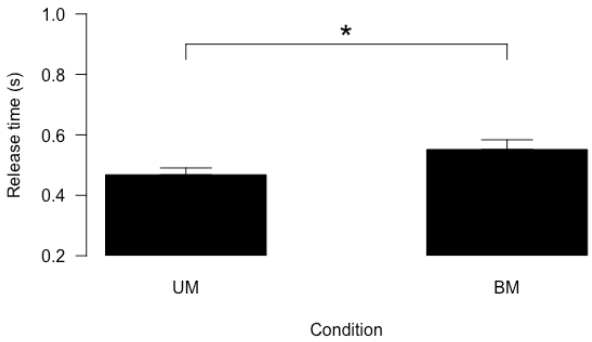


Figure 7.5: Mean release time (± SE) for UM and BM conditions.

Hold height

Analysis of hold height revealed no significant effect of group ($F(2, 52) = 0.15$, p = 0.86; YA = 261mm; OA G = 264mm; OA P = 267mm), hand ($F(1, 364) = 0.04$, p = 0.85, ND = 264mm; D = 264mm), or mass ($F(1, 364) = 0.06$, p = 0.80; L = 264mm; H = 263mm), but there was a significant effect of condition ($F(1, 364) = 7.00$, p = 0.009, UM = 262mm; BM = 265mm) with an increased hold height during BM lifts (figure 7.6). There was also a significant group * mass interaction ($F(2, 364) = 3.70$, p = 0.026) present. Data was collapsed across condition and hand to explore the group * mass interaction, one-way ANOVAs were used to test group differences within L and H masses and pairwise tests were used to explore within group differences, but no post-hoc tests reached levels of significance (p > 0.05). No further two, three or four-way effects were present.

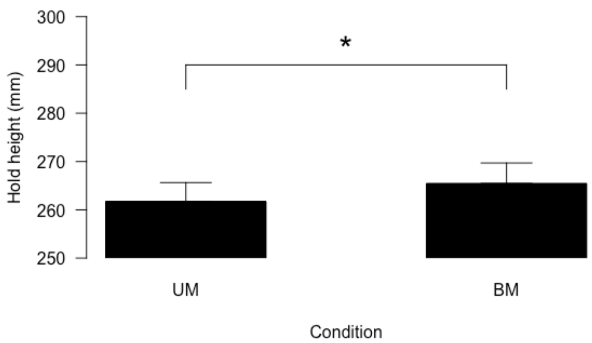


Figure 7.6: Mean hold height (± SE) for UM and BM conditions.

Path length

A log transformation of path length was necessary to normalise the model residuals and was used for all statistical analysis. The results for path length showed no significant main effect of group ($F(2, 52) = 2.21$, $p = 0.12$; YA = 21.8mm; OA G = 20.6mm; OA P = 18.2mm) or condition ($F(1, 364) = 0.15$, $p = 0.70$, UM = 20.6mm; BM = 20.6mm). The analysis did reveal a significant effect of hand ($F(1, 364) = 14.0$, $p < 0.001$, ND = 21.3mm; D = 19.9mm), with an increased path length for the ND hand and an effect of mass ($F(1, 364) = 4.92$, $p = 0.03$, L = 20.1mm; H = 21.1mm), with an increased path length for heavy objects. No further two, three or four-way interactions were present.

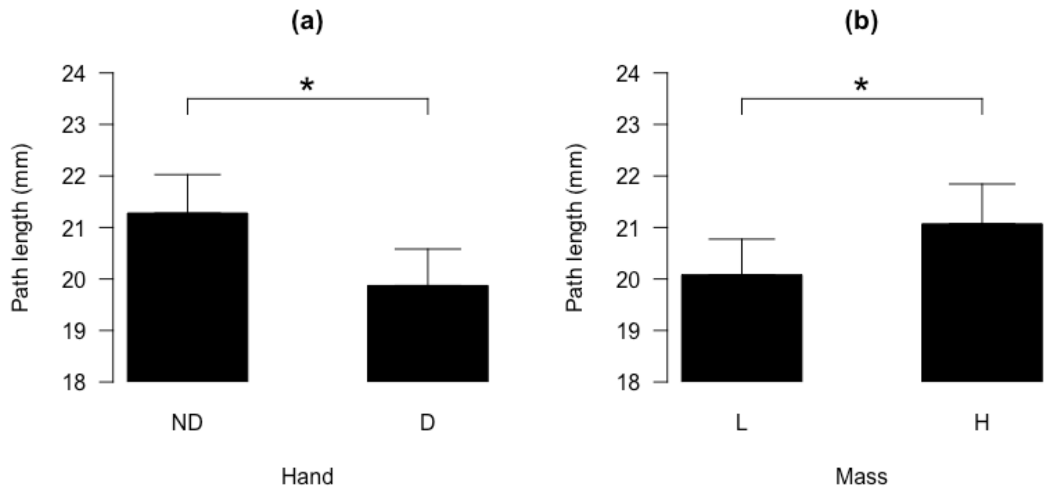


Figure 7.7: Mean path length (± SE) during the stable phase for (a) ND and D hands (b) L and H masses.

Peak grip force

A log transformation of peak grip force was used to test statistical significance. Analysis of the data revealed a significant main effect of group ($F(2, 52) = 11.20$, $p < 0.001$; YA = 7.9N; OA G = 13.6N; OA P = 15.7N) and mass ($F(1, 364) = 264$, $p < 0.001$, L = 9.6N; H = 14.3N) but no main effect of condition ($F(1, 364) = 0.18$, $p = 0.67$, UM = 12.2N; BM = 11.7N) or hand ($F(1, 364) = 0.55$, $p = 0.46$; ND = 12.1N; D = 11.9N), there was also a group * condition interaction ($F(2, 364) = 5.94$, $p = 0.003$) present which was further explored.

Data was collapsed across hand and mass to explore the group * condition interaction, one-way ANOVAs were used to test group differences within UM and BM conditions. Analysis on the UM data found a significant effect of group ($F(2, 52) = 6.02$, $p = 0.004$) with subsequent pairwise comparisons revealing a reduced peak GF for YA compared to OA G ($p < 0.001$, d = 1.34) and OA P ($p = 0.005$, $d = 1.55$), but no differences between OA G and OA P ($p = 1.0$, $d = 0.16$). Analysis within BM also found a significant effect of group ($F(2, 52) = 6.74$, $p = 0.003$), with pairwise comparisons again finding a reduced peak GF for YA compared to OA G ($p < 0.001$, $d = 1.18$) and OA P ($p = 0.005$, $d = 1.5$), but no differences between OA G and OA P ($p = 0.94$, $d = 0.39$). The within group analysis found a small, but significant increase in peak GF for YA during BM conditions ($p = 0.008$, $d = 0.66$), a decrease in peak GF for OA G during BM conditions ($p = 0.04$, $d = 0.45$), but no change for OA P between UM and BM conditions ($p = 0.55$, $d = 0.20$), see figure 7.8b.

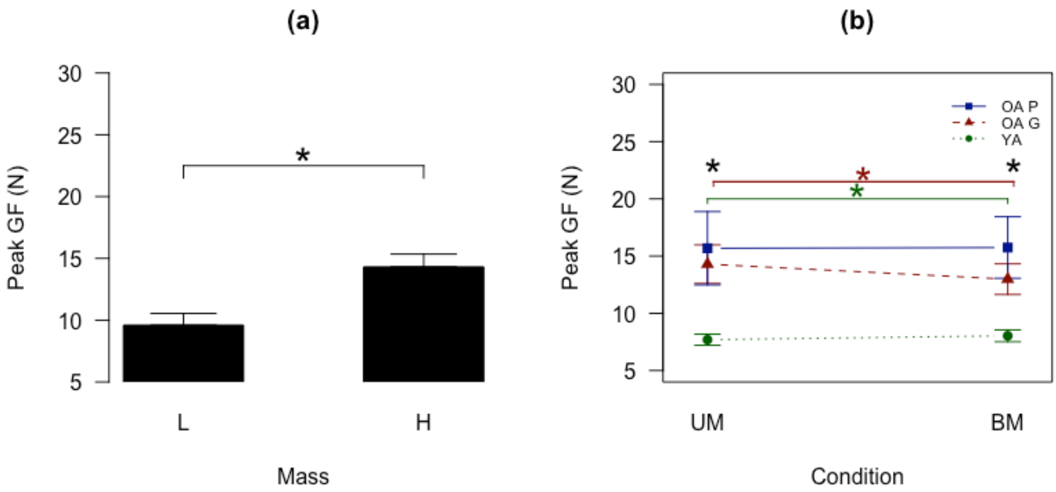


Figure 7.8: Mean peak grip force (±SE) for (a) L and H masses (b) YA, OA G and OA P across UM and BM conditions collapsed across hand and mass.

Time to peak grip force

A log transformation of time to peak grip force was used for all statistical testing. The results revealed no significant effect of group ($F(2, 52) = 2.22$, $p = 0.12$; YA = 0.97s; OA G = 1.20s; OA P = 1.20s), hand ($F(1, 364) = 1.63$, $p = 0.20$; ND = 1.07s; D = 1.17s) or mass ($F(1, 364) = 1.27$, $p = 0.26$; L = 1.12s; H = 1.15s) but a significant effect of condition ($F(1, 364) = 9.41$, $p = 0.002$, UM = 1.06s; BM = 1.17s), with an increased time to peak GF for bimanual conditions. No two, three or four-way effects were present (see appendix 9.5 table 9.31 for further details).

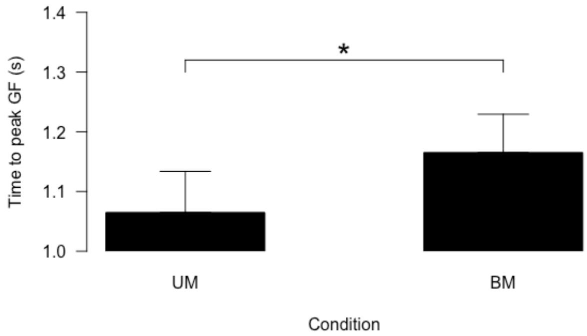


Figure 7.9: Mean time to peak GF (± SE) for UM and BM conditions.

Peak load force

A log transformation of peak load force was necessary for analysis to normalise the model's residuals. The results revealed no significant effect of group ($F(2, 52) = 0.32$, $p = 0.73$; YA = 3.61N; OA G = 3.55N; OA P = 3.58N), condition ($F(1, 364) = 3.38$, $p = 0.07$, UM = 3.60N; BM = 3.56N) or hand ($F(1, 364) = 0.21$, $p = 0.65$; ND = 3.57N; D = 3.58N), but, as anticipated, a significant effect of mass ($F(1, 364) = 7700$, $p < 0.001$, L = 2.42N; H = 4.73N). No two, three or four-way interactions were present.

Grip force to load force ratio at the start of the lift

A log transformation of grip force to load force ratio (GF:LF) was used for statistical testing. The results revealed a significant effect of group ($F(2, 52) = 11.9$, $p < 0.001$; YA = 2.21; OA G = 4.06; OA P = 4.52) and mass ($F(1, 364) = 46.5$, $p < 0.001$, L = 3.95; H = 3.01), but not of condition ($F(1, 364) = 0.27$, $p = 0.61$, UM = 3.54; BM = 3.41) or hand ($F(1, 364) = 0.85$, $p = 0.36$; ND = 3.53; D = 3.43). There was also a group * condition interaction present ($F(2, 364) = 4.81$, $p = 0.009$), thus exploration of this took priority over exploring the main effect of group. Data was collapsed across hand and mass before one-way ANOVAs were ran within UM and BM conditions. The ANOVA ran within the UM condition revealed a significant effect of group ($F(2, 52) = 5.68$, $p = 0.006$), with follow up pairwise comparisons showing YA have a reduced GF:LF compared to OA G ($p < 0.001$, $d = 1.41$) and OA P ($p = 0.006$, $d = 1.50$), but no differences were present between OA G and OA P ($p = 1.0$, $d = 0.11$). Similarly, the ANOVA ran on BM data found a significant effect of group ($F(2, 52) = 5.81$, $p = 0.005$), with follow up pairwise comparisons revealing a lower GF:LF for YA compared to OA G ($p < 0.001$, $d = 1.25$) and OA P ($p < 0.006$, $d = 1.49$) but no differences between OA G and OA P (p = 1.0, *d* = 0.30). The within group analysis revealed a slight increase in GF:LF during BM conditions for YA (p = 0.02, *d* = 0.57), OA G showed a decrease in GF:LF during BM conditions (p = 0.04, *d* = 0.45) but there was no change for OA P between conditions (p = 0.63, *d* = 0.15) see figure 7.10b.

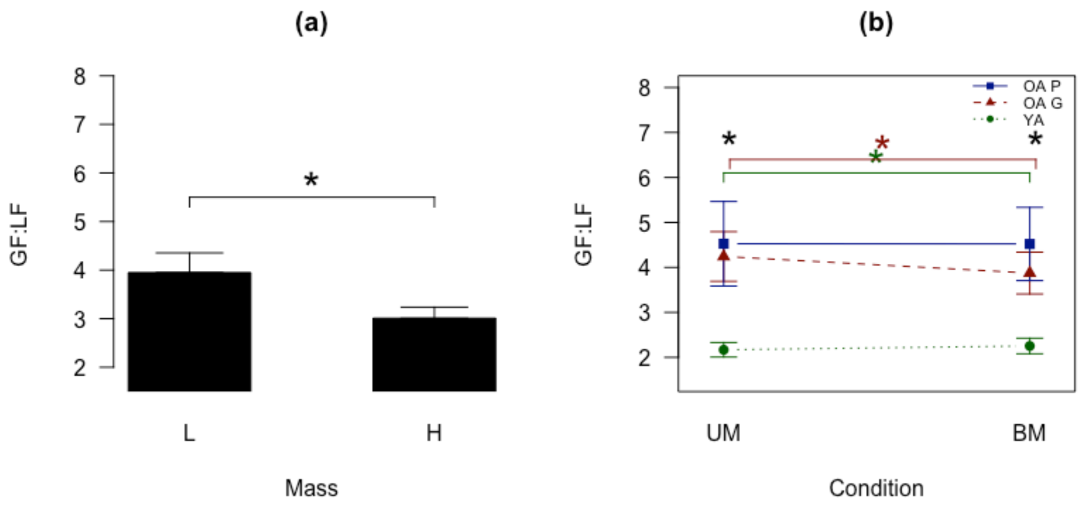


Figure 7.10: Mean GF:LF (± SE) over the first 200ms of the lift for (a) L and H masses (b) YA, OA G and OA P across UM and BM conditions, data collapsed across hand and mass.

Grip force to load force ratio during the stable phase

A log transformation of GF:LF ratio during the stable phase was used for statistical testing. The results revealed a significant main effect of group ($F(2, 52) = 11.7$, $p < 0.001$; YA = 1.85; OA G = 3.21; OA P = 3.87) and mass ($F(1, 364) = 58.0$, $p < 0.001$; L = 3.27; H = 2.43), but not of condition ($F(1, 364) = 0.89$, p = 0.34, UM = 2.92; BM = 2.78) or hand ($F(1, 364) = 1.00$, p = 0.32; ND = 2.78; D = 2.92). There was also a group * condition interaction present ($F(2, 364) = 4.61$, p = 0.011), which was prioritised for further analysis. Mirroring the post-hoc analysis used for GF:LF during the start of the lift, data was collapsed across hand and mass before one-way ANOVAs were ran on UM and BM data. Testing revealed a significant effect of group within UM conditions ($F(2, 52) = 6.84$, p = 0.002), with follow up pairwise comparisons showing YA had a lower GF:LF during the stable phase compared to OA G ($p < 0.001$, *d* = 1.40) and OA P (p = 0.005, *d* = 1.57), but no differences were present between OA G and OA P (p = 1.0, *d* = 0.23). Analysis on BM data also found a significant effect of group ($F(2, 52) = 6.68$, p = 0.003), with pairwise comparisons showing a decrease GF:LF for YA compared to OA G (p = 0.001, *d* = 1.15) and OA P (p = 0.009, *d* = 1.42) but no difference between OA G and OA P (p = 0.95, *d* = 0.39). Post-hoc testing within groups revealed YA use an increased GF:LF during BM lifts (p = 0.02, *d* = 0.57), OA G show a reduction in GF:LF during BM conditions (p = 0.04, *d* = 0.44) and OA P show no difference between UM and BM conditions (p = 0.67, *d* = 0.13), see figure 7.11b.

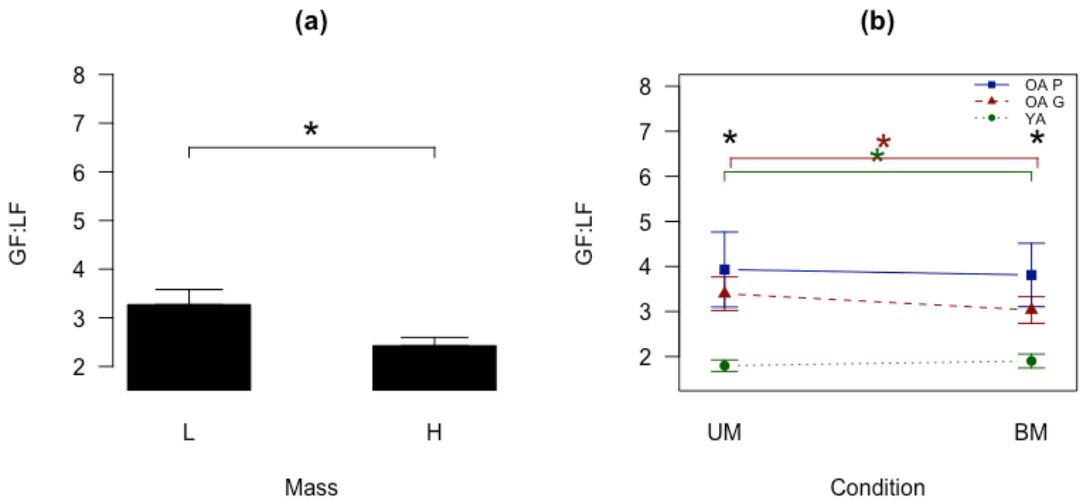


Figure 7.11: Mean GF:LF (± SE) during the stable phase of the lift for (a) L and H masses (b) YA, OA G and OA P across UM and BM conditions, data collapsed across hand and mass.

Safety margin

Based on assumption testing results, a log transformation of safety margin was carried out for all statistical testing. The results revealed a significant main effect of group ($F(2, 52) = 4.71$, p = 0.013; YA = 2.89N; OA G = 5.58N; OA P = 6.26N) and mass ($F(1, 364) = 17.5$, p < 0.001; L = 4.26N; H = 5.22N), but not of condition ($F(1, 364) = 2.88$, p = 0.09, UM = 4.93N; BM = 4.54N) or hand ($F(1, 364) = 1.29$, p = 0.26; ND = 4.55N; D = 4.92N). There was also a group * condition interaction present ($F(2, 364) = 4.22$, p = 0.02), which was prioritised for post-hoc analysis over the main effect of group. Data was collapsed across hand and mass before one-way ANOVAs were ran on UM and BM datasets. The results revealed significant group differences within UM conditions ($F(2, 52) = 4.73$, p = 0.01), with follow up pairwise comparisons showing a lower safety margin for YA compared to OA G (p = 0.01, *d* = 0.97) and OA P (p = 0.02, *d* = 1.14) but no difference between OA G and OA P (p = 1.0, *d* = 0.08). Analysis of BM data also found a significant effect of group ($F(2, 52) = 3.69$, p = 0.03), but levels of significance were not reached in pairwise comparisons between YA and OA G (p = 0.09, *d* = 0.66), YA and OA P (p = 0.08, *d* = 1.05) or OA G and OA P (p = 1.0, *d* = 0.25). Testing within groups revealed no significant difference between UM and BM conditions for YA (p = 0.07, *d* = 0.43) or OA P (p = 0.58, *d* = 0.17) but there was a decrease in SM for OA G when performing BM lifts (p = 0.18, *d* = 0.52), see figure 7.12b. No further two, three or four-way interactions were present (see appendix 9.5 table 9.35 for further details).

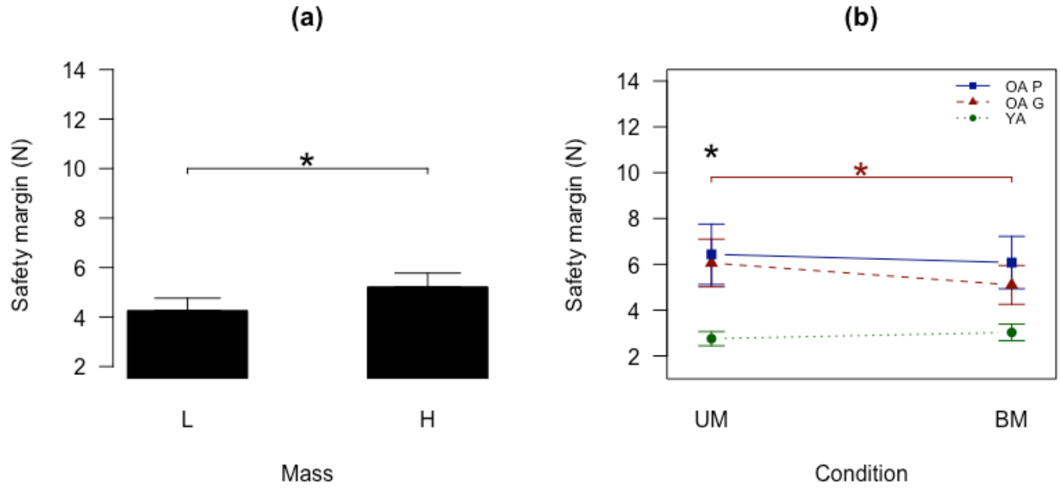


Figure 7.12: Mean safety margin (± SE) during the stable phase of the lift for (a) L and H masses (b) YA, OA G and OA P across UM and BM conditions, data collapsed across hand and mass.

Peak cross-correlation coefficient

Analysis on the cross-correlation coefficient between change in grip force and change in load force revealed a significant main effect of group ($F(2, 52) = 6.99$, p = 0.002) and mass ($F(1, 364) = 32.5$, p < 0.001, L = 0.62; H = 0.65), but not of condition ($F(1, 364) = 1.03$, p = 0.31, UM = 0.64; BM = 0.63) or hand ($F(1, 364) = 1.41$, p = 0.24; ND = 0.64; D = 0.63). Pairwise comparisons between groups revealed a significant effect between YA (mean = 0.69) and OA G (mean = 0.63) (p = 0.04, *d* = 0.66), YA and OA P (mean = 0.56) (p = 0.001, *d* = 1.49) and OA G and OA P (p = 0.047, *d* = 0.73), figure 7.13a shows the difference between all three groups. There were no two, three or four-way interactions present, see appendix 9.5 table 9.36 for further details.

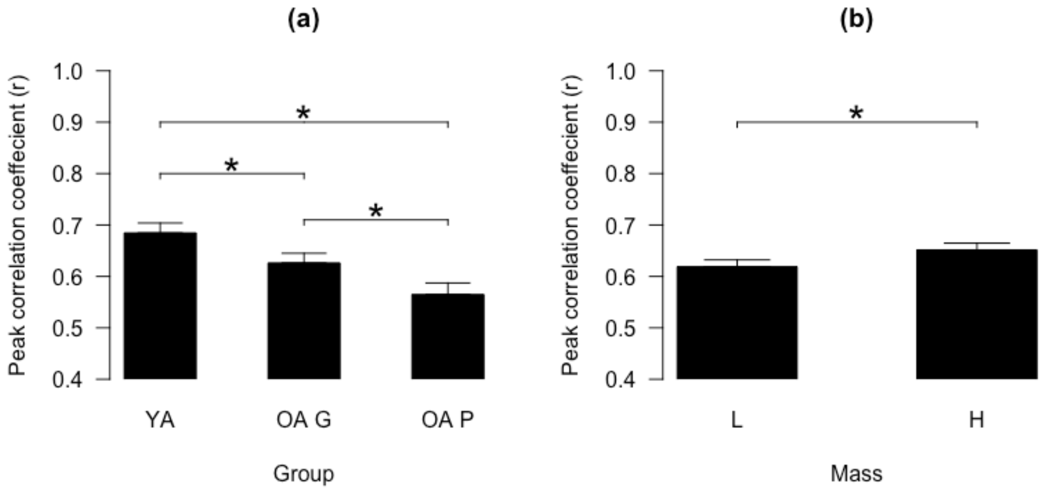


Figure 7.13: Mean (± SE) cross-correlation coefficient *for (a) YA, OA G and OA P (b) L and H masses.*

Time-shift of peak cross-correlation

Analysis of the time-shift of the peak cross-correlation revealed no significant main effect of group ($F(2, 52) = 0.30$, p = 0.74; YA = 8.67ms; OA G = 2.64ms; OA P = 8.66ms), condition ($F(1, 364) = 0.34$, p = 0.56, UM = 7.21ms; BM = 5.10ms), hand ($F(1, 364) = 0.15$, p = 0.70; ND = 5.50ms; D = 6.82ms) or mass ($F(1, 364) = 0.26$, p = 0.61; L = 7.24ms; H = 5.07ms), but there was a significant interaction between group * hand ($F(2, 364) = 3.70$, p = 0.026). Data was collapsed across condition and mass for post-hoc testing on the group * hand interaction. Subsequent ANOVAs within ND found no differences between groups ($F(2,52) = 1.23$, p = 0.30). No significant differences were found with D hand either ($F(2,52) = 0.50$, p = 0.61). Testing across hand within each group revealed no significant differences between hands for YA (p = 0.17, $d = 0.32$) or OA G (p = 0.39, $d = 0.18$), but OA P showed a significant change in time-shift (p = 0.015, $d = 0.88$) with GF scaling in advance of LF when using their D hand, see figure 7.14. No further two, three or four-way interactions were present, see appendix 9.5 table 9.37 for further details.

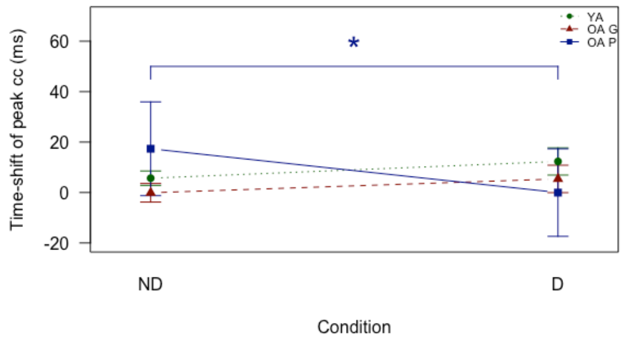


Figure 7.14: Mean (± SE) time-shift of peak cross-correlation for YA, OA G and OA P across D and ND hands, data is collapsed across condition and mass.

7.3.3 EMG analysis

Dynamic phase

The NMF analysis ran for the full EMG dataset for YA, OA G and OA P during the dynamic lifting phase returned an explained variance of 0.964 when compared to the original dataset, indicating a strong representation of the original data (D'Avella et al., 2006). Figure 7.15 shows the invariant muscle weightings that contribute to each synergy during the dynamic phase – from initial contact to the start of the stable phase.

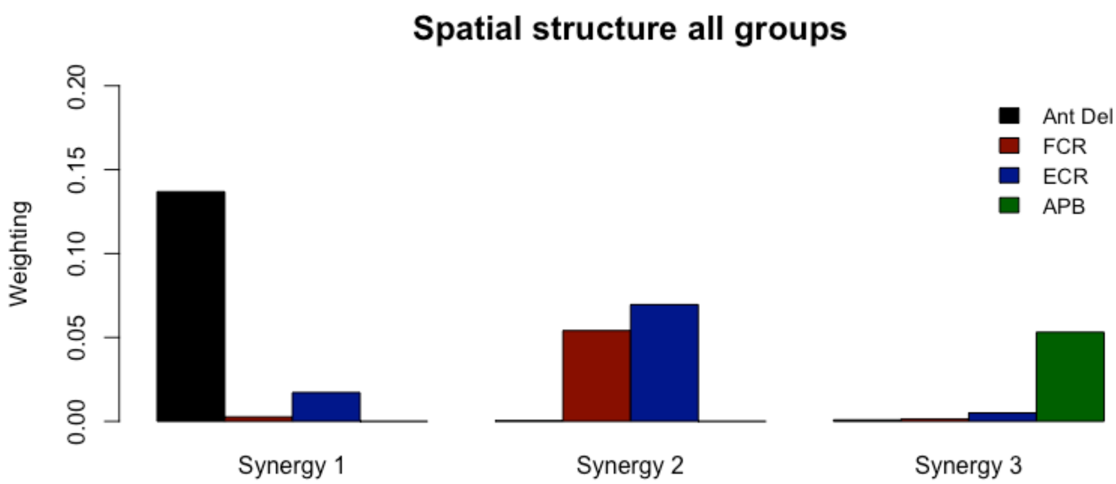


Figure 7.15: Invariant muscle weightings for the NMF ran on the dataset across YA, OA G and OA P. The coloured bars represent the associated muscle component for each muscle synergy: Ant Del = Anterior Deltoid; FCR = Flexor Carpi Radialis; ECR = Extensor Carpi Radialis; APB = Abductor Pollicis Brevis).

Figure 7.16 shows the temporal weightings for muscle synergies one, two and three for YA, OA G and OA P averaged across conditions, hand and mass. This provides a visual guide for the statistical analysis that follows. Note the changes in temporal profiles for synergies two and three between YA, OA G and OA P.

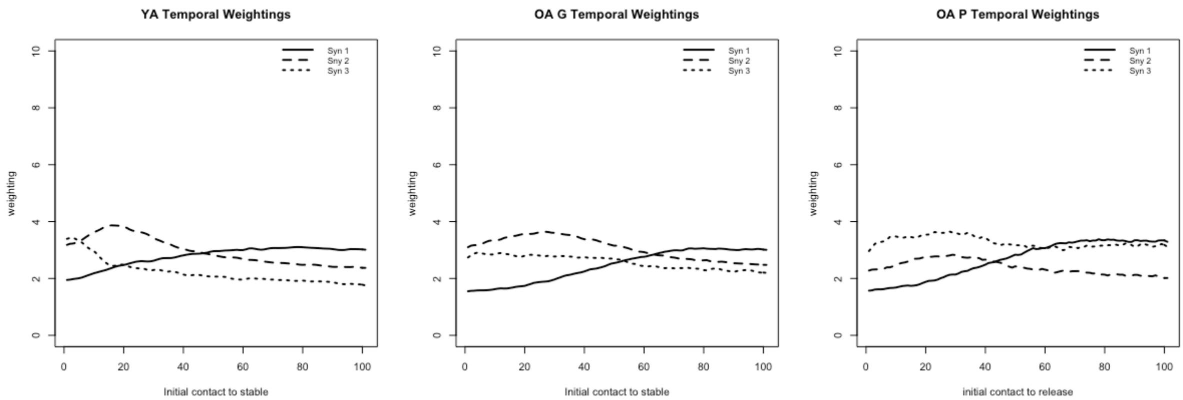


Figure 7.16: Mean temporal weightings for YA and OA G and OA P from initial contact to the start of the stable phase (normalised over 101 datapoints).

Table 7.1 below shows the results for the Pearson's correlations ran between muscle synergies one, two and three for YA, OA G and OA P to determine how independent or coupled each synergy's activation was in relation to one another. These values are averaged across conditions, hand and mass. Note the increased correlation between muscle synergies two and three (correlation 2) for OA G and OA P.

Table 7.1: Mean (± SE) correlation coefficient between each muscle synergy for YA, OA G and OA P during the dynamic lifting phase.

	Correlation 1 (S1 ~ S2)	Correlation 2 (S2 ~ S3)	Correlation 3 (S1 ~ S3)
YA	- 0.18 ± 0.17	0.12 ± 0.16	- 0.14 ± 0.16
OA Good	- 0.27 ± 0.24	0.19 ± 0.21	- 0.11 ± 0.26
OA Poor	- 0.31 + 0.23	0.29 + 0.23	- 0.11 ± 0.29

The mixed-effects model ran on correlation one, assessing the temporal relationship between synergy 1 and synergy 2 found no significant main effect of group ($F(2, 41) = 2.01$, p = 0.15; YA = - 0.18; OA G = - 0.27; OA P = - 0.31), condition ($F(1, 240) = 1.53$, p = 0.22; UM = - 0.25; BM = - 0.24) or hand ($F(1, 240) = 0.54$, p = 0.46; ND = - 0.23; D = - 0.26), but there was a significant effect of mass ($F(1, 240) = 10.36$, p = 0.002; L = - 0.27; H = - 0.22). There were no two, three or four-way effects present (see appendix 9.5 table 9.38 for further details).

Analysis on correlation two, assessing the temporal relationship between synergy 2 and synergy 3, revealed a significant main effect of group ($F(2, 41) = 5.65$, p = 0.007; YA = 0.12; OA G = 0.19; OA P = 0.29), but no effect of condition ($F(1, 240) = 0.67$, p = 0.41; UM = - 0.20; BM = - 0.19), hand; ($F(1, 240) = 1.50$, p = 0.22; ND = 0.21; D = 0.18) or mass; ($F(1, 238) = 0.02$, p = 0.89; L = 0.19; H = 0.20). Pairwise comparisons of group revealed a significant increase in correlation values between YA and OA P (p = 0.006, d = 1.57), but levels of significance were not reached between YA and OA G (p = 0.08, d = 0.62) or between OA G and OA P (p = 0.20, d = 0.75) once a Bonferroni correction was applied. No further two, three or four-way effects were present (see appendix 9.5 table 9.39 for further details).

Analysis on correlation three found no significant main effect of group ($F(2, 41) = 0.22$, p = 0.80; YA = - 0.14; OA G = - 0.11; OA P = - 0.11), condition ($F(1, 240) = 1.62$, p = 0.20; UM = - 0.11; BM = - 0.13), mass; ($F(1, 240) = 2.25$, p = 0.13; L = - 0.14; H = - 0.10) or hand; ($F(1, 240) = 2.08$, p = 0.15; ND = - 0.15; D = - 0.09). There was a significant group * condition interaction ($F(2, 240) = 3.41$, p = 0.035), which was explored. Data was collapsed across hand and mass before one-way ANOVAs were ran on UM and BM data. The analysis within UM found no significant differences between groups ($F(2, 40) = 0.33$, p = 0.72), the same was true for BM conditions ($F(2, 41) = 0.62$, p = 0.54). Testing differences within groups revealed an increased negative correlation for YA when moving to BM conditions (p = 0.002, d = 0.93, UM = - 0.10; BM = - 0.19), but no such adaptations were present with OA G (p = 0.27, d = 0.09, UM = - 0.15, BM = - 0.13) and OA P (p = 0.98, d = 0.01, UM = - 0.11; BM = - 0.11).

Stable phase

The NMF analysis ran for the full EMG dataset for YA, OA G and OA P during the stable phase returned an explained variance of 0.973 when compared to the original dataset, indicating a strong representation of the original data. Figure ten shows the invariant muscle weights that contribute to each synergy during the stable phase – from the start to the end of the stable phase. Figure 7.17 shows the invariant muscle weightings that contribute to each synergy during the stable phase of the task.

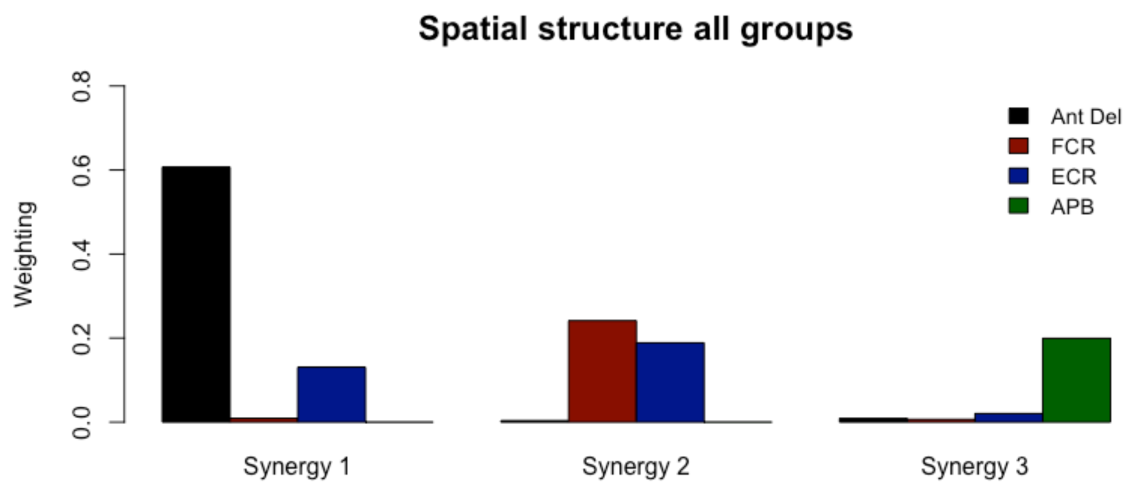


Figure 7.17: Invariant muscle weightings for the NMF ran on the dataset across YA, OA G and OA P. The coloured bars represent the associated muscle component for each muscle synergy: Ant Del = Anterior Deltoid; FCR = Flexor Carpi Radialis; ECR = Extensor Carpi Radialis; APB = Abductor Pollicis Brevis.

Figure 7.18 shows the temporal weightings for muscle synergies one, two and three, during the stable phase, for YA, OA G and OA P averaged across conditions, hand and mass. Similar temporal profiles are present across all group.

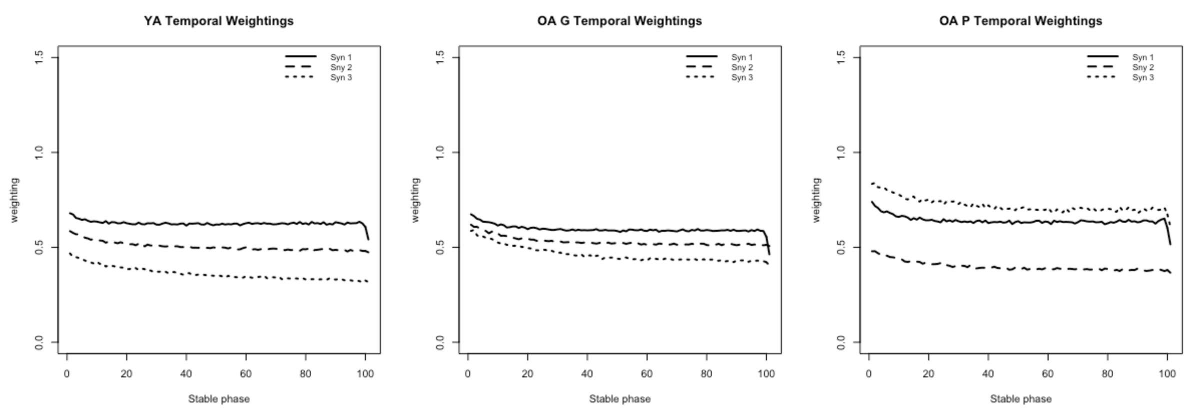


Figure 7.18: Mean temporal weightings for YA and OA G and OA P for the stable phase (normalised over 101 datapoints).

Table 7.2 below shows the results for the Pearson's correlations ran between muscle synergies one, two and three for YA, OA G and OA P during the stable phase. These values are averaged across conditions, hand and mass.

Table 7.2: Mean (± SE) correlation coefficient between each muscle synergy for YA, OA G and OA P during the stable phase.

	Correlation 1 (S1 ~ S2)	Correlation 2 (S2 ~ S3)	Correlation 3 (S1 ~ S3)
YA	- 0.19 ± 0.13	0.10 ± 0.17	0.00 ± 0.10
OA Good	- 0.16 ± 0.13	0.11 ± 0.18	0.00 ± 0.13
OA Poor	- 0.16 ± 0.14	0.11 ± 0.20	0.00 ± 0.11

Analysis of correlation one during the stable phase found no significant main effect of group ($F(2, 41) = 0.51$, $p = 0.60$; YA = - 0.19; OA G = - 0.16; OA P = - 0.16), condition ($F(1, 240) = 1.43$, $p = 0.23$; UM = - 0.16; BM = - 0.18), hand ($F(1, 240) = 1.97$, $p = 0.16$; ND = - 0.16; D = - 0.19) or mass ($F(1, 240) = 0.03$, $p = 0.86$; L = - 0.17; H = - 0.17). However, there was a group * condition interaction present ($F(2, 240) = 4.69$, $p = 0.01$). Data was collapsed across hand and mass before one-way ANOVAs were ran across UM and BM data to assess any group differences. The analysis revealed no significant group differences within UM ($F(2, 40) = 1.77$, $p = 0.18$) or BM conditions ($F(2, 41) = 1.50$, $p = 0.24$). Comparisons within group found no significant difference between UM and BM conditions for YA ($p = 0.08$, $d = 0.46$, UM = - 0.17; BM = - 0.21), OA G ($p = 0.10$, $d = 0.56$, UM = - 0.12; BM = - 0.18) or OA P ($p = 0.09$, $d = 0.59$, UM = - 0.18; BM = - 0.14). No further two, three or four-way interactions were present, see appendix 9.5 table 9.41 for further details.

Analysis of correlation two found no significant main effects of group ($F(2, 41) = 0.14$, $p = 0.87$; YA = 0.10; OA G = 0.11; OA P = 0.11), condition ($F(1, 240) = 0.50$, $p = 0.48$; UM = 0.11; BM = 0.10), hand ($F(1, 240) = 1.79$, $p = 0.18$; ND = 0.12; D = 0.09) or mass ($F(1, 240) = 0.00$, $p = 1.00$; L = 0.11; H = 0.11). There was a significant hand * mass interaction ($F(1, 240) = 6.50$, $p = 0.01$) and group * condition * hand interaction ($F(2, 240) = 4.07$, $p = 0.018$) but no significant effects were present when analysing underlying two-way interactions. No further two, three or four-way interactions were present, see appendix 9.5 table 9.42 for further details.

Analysis of correlation three found no significant main effect of group ($F(2, 41) = 0.04$, p = 0.96; YA = 0.00; OA G = 0.00; OA P = 0.00), condition ($F(1, 240) = 3.38$, p = 0.07; UM = 0.01; BM = - 0.01), hand ($F(1, 240) = 0.03$, p = 0.85; ND = - 0.00; D = 0.00) or mass ($F(1, 240) = 0.24$, p = 0.62; L = 0.01; H = - 0.00). No two, three or four-way interactions were present, see appendix 9.5 table 9.43 for further details.

7.3.4 Biometric variables

The ANOVA assessing max pinch strength found no significant effect of group ($F(2, 52) = 0.63$, p = 0.54, $\eta 2 = 0.18$; YA = 8.16N; OA G = 7.68N; OA P = 8.32N), or hand ($F(1, 52) = 3.72$, p = 0.06, $\eta 2 = 0.18$; ND = 7.83N; D = 8.14N) and no group * hand interaction ($F(2, 52) = 1.27$, p = 0.29, $\eta 2 = 0.05$).

Analysis of the Semmes-Weinstein monofilament test found a significant main effect of group ($F(2, 52) = 7.70$, p = 0.001, $\eta 2 = 0.46$) but not of hand $F(1, 52) = 3.19$, p = 0.08, $\eta 2 = 0.06$; ND = 0.20g; D = 0.25g) and no group * hand interaction was present ($F(2, 52) = 1.57$, p = 0.22, $\eta 2 = 0.06$). Pairwise comparisons between groups found a significantly lower Semmes-Weinstein score for YA (mean = 12g) compared to OA G (mean = 0.23g) (p = 0.037, d = 0.78) and OA P (mean = 0.40g) (p = 0.05 = d =1.20), but no difference between OA G and OA P (p = 0.36, d = 0.66).

Analysis of Purdue Pegboard scores revealed a significant main effect of group (F(2, 52) = 32.2, $p < 0.001$, $\eta 2 = 0.72$, YA = 13.0, OA G = 12.2, OA P = 9.02) and of hand (F(2, 104) = 76.8, $p < 0.001$, $\eta 2 = 0.60$), but no group * hand interaction ($F(4, 104) = 0.80$, p = 0.53, $\eta 2 = 0.03$). Pairwise comparisons between groups found significant differences between YA (mean = 13.0) and OA P (mean = 9.0) ($p < 0.001$, d = 3.06) and between OA G (mean = 12.2) and OA P ($p < 0.001$, d = 2.58), but no statistical difference between YA and OA G (p = 0.15, d = 0.61). Pairwise comparison within hand found significant differences between all three conditions: D (mean = 13.0) and ND (mean 12.2) (p = 0.001, d = 0.46), D and BM (mean = 10.3) ($p < 0.001$, d = 1.68), ND and BM ($p < 0.001$, d = 1.23).

7.4 Discussion

The aims of this experiment were to explore grasping variables that distinguish OA with good manual dexterity, from those with poor levels of manual dexterity. Secondly, to assess if OA with good levels of manual dexterity show similar grasping strategies to YA, or new, emergent strategies as a function of age. To answer the research questions a cluster analysis was applied to the OA sample sub-dividing them into two subgroups (OA G and OA P). Figure 7.1 shows the success of this approach, the two subgroups show considerable overlap in age, but the new subgroups represent far less variability in manual dexterity (within sum of squares reduced from 2014 with one cluster to 750 with two clusters). The key findings from the subsequent analyse were: i) The maximum cross-correlation coefficient between GF and LF was the only grasping variable that separated OA G from OA P. ii) There were differences in muscle synergy relationships between OA G and OA P during the dynamic phase, but these did not reach levels of significance ($p > 0.05$). iii) OA G displayed different temporal and kinetic grasping strategies compared to YA, indicating new emergent strategies as a result of healthy ageing. The following section discusses the findings in more detail.

7.4.1 Differences between older adults with good and poor manual dexterity

This experiment aimed to explore the kinematic, kinetic and muscular synergy relationships that separate OA G and OA P during anticipatory and reactive phases of grasping. To achieve this 15 variables, that have previously shown age-related changes (Cole, 1991; Cole and Beck, 1994; Lowe, 2001; Lin et al., 2014) and differences in clinical populations (Duque et al., 2003; McDonnell et al., 2006), were included within the analysis. These variables were combined with EMG analysis assessing changes in muscle synergy relationships between the groups. The results show that only one variable, from those analysed, significantly distinguished grasping strategies used by OA G and OA P populations – a reduced peak cross-correlation coefficient between GF and LF during the anticipatory phase of grasping.

A fundamental principle of successful grasping and lifting is ensuring the object remains securely gripped between the digits and thumb throughout the task. To maintain a secure grasp, GF levels must maintain a value above a point where the object begins to slip; known as the slip ratio (Johansson and Westling, 1984). The goal of maintaining GF above the slip ratio is most challenging at the start of the lift when the individual has to anticipate intrinsic object properties and the subsequent levels of friction they have achieved with their digit placement (Nowak et al., 2001). As the object begins accelerating upwards LF is ever-changing. There is strong evidence to suggest that levels of GF during this time are dependent on individuals anticipating LF values and scaling GF in advance (Grover et al., 2019), the success of this ability can be quantified using cross-correlation analysis between GF and LF (Duque et al., 2003; McDonnell et al., 2006). Figure 7.13a shows the peak cross-correlation data for YA, OA G and OA P, this figure displays the reduced ability OA P have to dynamically scale changes in GF to changes in LF. The medium effect size between OA G and OA P ($d = 0.73$) indicates the ability to effectively scale GF to changes in LF at the start of the lift is notably diminished in OA P. This group difference was apparent across UM - BM conditions, ND - D hands and varying masses indicating this is a consistent effect across many variants of grasping. To the authors' knowledge this is the first time cross-correlation analysis has been carried out during the initial stages of a grasp-lift-replace task within a healthy, ageing population. The finding provides strong evidence that OA with lower levels of manual dexterity exhibit reduced anticipatory grasping control. This discovery is in line with previous research conducted within clinical populations where individuals' who suffer from reduced sensorimotor control also display reduced anticipatory control (Duque et al., 2003; McDonnell et al., 2006). There was also a significant difference between YA and OA G in cross-correlation values, despite no significant difference between the YA and OA G groups in Perdue Pegboard scores. Based on this finding, an argument could be made that all OA show a reduced capacity to scale GF to changes in LF (figure 7.13a), but a critical point may exist, past which, manual dexterity becomes significantly affected.

7.4.2 Adaptations in muscle synergy relationships between groups

In line with the findings from experiment two (chapter 6), there was a significant main effect of group when analysing the temporal activations of the muscle synergies in the forearm and hand (Correlation 2, mean r value: YA = 0.12, OA G = 0.19, OA P = 0.29). Pairwise comparisons found a significant difference between YA and OA P and medium to large effect sizes between all three groups ($d = 0.62$ to 1.57), but once a Bonferroni adjustment was applied these differences were not statistically significant between YA – OA G or OA G – OA P ($p > 0.05$). The following section considers this finding, albeit non-significant between all three groups it does occur during the same timepoint where there is a significant difference in anticipatory force control between all three groups and may explain the behavioural finding. The muscle synergy results indicate OA P show an increased, positive correlation between muscle synergy two (ECR, FCR) and muscle synergy three (APB) during the dynamic phase of the lift compared to OA G and YA. Figure 7.16 displays the mean temporal profiles for each group, allowing a clearer understanding of where differences occurred. In the early stages of the lift (datapoints 0 – 40) YA show opposing activation patterns between synergy two and synergy three, before the two signals begin to show greater agreement and run in parallel (datapoints 41 – 101). OA G show less asynchronous patterns in early stages of lifting between synergy two and synergy three, whereas OA P show highly similar temporal profiles between synergies two and three throughout the dynamic lifting phase. These findings suggest YA are able to selectively recruit muscle synergies independently of each other, this ability is reduced in OA G and further diminished in OA P, who appear less able to independently recruit APB and muscles in the forearm (ECR and FCR).

Neuromuscular control of the hand is complex, with singular muscles in the forearm creating movement of more than one digit (known as finger enslaving), meaning selective activation of multiple muscles is often required to independently control one digit (Santello et al., 2013) – this highlights the importance of being able to independently and selectively activate muscles when performing fine, grasping tasks. On top of the mechanical constraints (finger enslaving), the hand has a higher level of neural constraints – TMS studies have shown cortical activation of the motor cortex results in flexion patterns across all digits that resemble endpoints similar to those used in grasping (Gentner and Classen, 2006), suggesting an unconscious, modular organisation of muscle activations may reside at a cortical level (Santello et al., 2013). The findings from the current study indicate OA P are less able to selectively activate distal muscles during grasping compared to YA, this may help explain their less-dextrous ability (lower Purdue Pegboard score) and reduced ability to scale GF to changes in GF (lower cross-correlation coefficients). Considering OA P showed no significant loss in strength or cutaneous sensitivity compared to OA G, it is unlikely that the two groups show considerable changes to mechanical constraints of the hand. Therefore, the reduced ability to selectively activate muscles seen in OA P, may represent a change in the unconscious, modular organisation of muscle activity at a cortical or sub-cortical level (Gentner and Classen, 2006).

7.4.3 Emergent grasping strategies in all older adults

Cole (2009) and Diermayr et al. (2011), in separate literature reviews, summarised that an increase in peak GF is one of the most robust findings between YA and OA. Increased peak grip force, GF:LF and safety margins have been reported across static (Cole, 1991; Cole and Beck, 1994) and dynamic (Danion et al., 2007) grasping tasks, changing object properties (Cole, 1991; Kinoshita, 1996) and grasping tasks where OA are seated and standing (Mallau and Simoneau, 2009). These findings are often considered to represent the deterioration in motor function we see in OA (Diermayr et al., 2011). However, previous literature has rarely taken measures of motor function, such as manual dexterity, and has not included it as a grouping factor as used in the current experiment. The findings from this experiment found both OA G and OA P show increased loading times, peak GF, GF:LF and safety margins compared to YA (figures 7.2a, 7.8b, 7.10b, 7.11b, 7.12b). Notably, statistical analysis of these variables presented no significant differences between the OA G and OA P groups, signifying these grasping adaptations are emergent with older age, but do not represent any deterioration in manual dexterity as a result of ageing. The consistent group differences for loading times, peak GF, GF:LF and safety margin across UM and BM tasks, both hands and differing object masses highlight how consistent these adaptations are in OA, regardless of changes in the grasping task. The longer loading time and increased GF profiles observed in all OA may represent a more conservative strategy used to grasp and lift objects, ensuring objects are not dropped.

7.4.4 Future directions in ageing & grasping research

The current experiment employed a novel approach to stratify OA based on manual dexterity scores. The findings suggest this approach has good merit for better understanding motor decline as a function of age. Future research should be cautious when selecting OA samples based purely on age, to represent populations with reduced motor function, as the current experiment shows no statistical difference in Purdue Pegboard scores between YA (M = 22.2 ± 2.59yrs) and OA G (M = 70.74 ± 7.76yrs). Sensorimotor tests such as the Perdue Pegboard, Semmes-Weinstein and grip strength measures are useful for subgrouping OA based on function and should be considered in future grasping research (Desrosiers et al., 1995; Murata et al., 2010). The current experiment selected the Purdue Pegboard test to quantify manual dexterity, this was chosen due to its high levels of test-retest reliability, and previous use assessing OA (Desrosiers et al., 1995; Desrosiers et al., 1999). The Purdue Pegboard also requires individuals to transport their limb, grasp and manipulate objects – challenging both gross and fine aspects of manual dexterity (Desrosiers et al., 1995). Nonetheless, finger kinematics observed during the Purdue Pegboard test do not perfectly represent the finger kinematics seen during ADL (Gonzalez et al., 2017), therefore future studies should also consider alternative strategies for quantifying levels of manual dexterity and individuals' functional capacity for performing ADL.

Based on findings from this experiment, future research should continue to explore anticipatory control (Diermayr et al., 2011) and muscle synergies in OA. The current study indicates NMF is a useful tool for assessing changes in muscle synergy patterns within OA subgroups. However, more research is needed, with larger sample sizes and an increased number of muscle measured to create a detailed picture of anticipatory control in the upper limb. Finally, the cluster analysis used in this experiment proved useful in reducing the variance in Purdue Pegboard scores within the OA sample and successfully created two sub-groups. The result, however, were uneven sample sizes and a smaller group representing OA with reduced manual dexterity (OA G = 24; OA P = 11), which limited the power to detect differences between OA G and OA P. Despite the limited power, anticipatory control was still deemed a significant factor separating OA G and OA P indicating the sample sizes were sufficient to detect changes in grasping strategies between groups of OA.

7.5 Conclusion

This experiment took the novel approach of dividing OA into subgroups with 'good' and 'poor' levels of manual dexterity, using the Perdue Pegboard as a measure of manual dexterity. The resulting analysis showed OA with reduced manual dexterity exhibit reduced anticipatory control during lifting. Specifically, OA P have a reduced ability to scale GF to changes in LF. At a muscular level, OA P also show a reduced ability to selectively activate distal muscles compared to YA, but differences between OA G and OA P did not reach levels of statistical significance. The minimal changes in pinch strength and cutaneous sensitivity between OA G and OA P indicate changes in grasping control strategies may symbolise adaptations to unconscious, neural modular muscle control at a cortical or subcortical level (Gentner and

Classen, 2006), rather than physiological changes in strength and touch. Previous research in ageing and grasping (Cole, 2009; Diermayr et al., 2011) has inferred a relationship between changes in force profiles (GF, GF:LF and safety margin) and reduced motor performance seen in OA. Findings from this experiment provide strong evidence that these kinetic changes are emergent grasping strategies synonymous with all OA but have little relation to reduced manual dexterity in OA.

Chapter 8 – General Discussion

8.1 Introduction

From 2008 to 2018 the UK experienced a 22% rise in individuals aged 65 and over (Office for National Statistics UK, 2019). As UK and global populations continue to age, the drive to keep them healthy and independent will become ever more important. Older adults' (OA) ability to perform activities of daily living (ADL) forms one crucial part of maintaining their independence – 15% of adults aged 65 – 69 struggle to perform one or more ADL, but this figure rises to 33% in OA 85+ years old, who subsequently require care. By 2040 the total number of disabled older people in the UK is projected to increase by 67% to 5.9 million (Age UK, 2019). Grasping and object manipulation play key roles in performing many ADL – such as dressing and eating (Murata et al., 2010; Vieluf et al., 2015). Thus, this thesis aimed to better understand grasping and object manipulation in OA by studying their behaviour during the grasp-lift-replace paradigm.

Grasp–lift–replace paradigms offer an insight into anticipatory and reactive mechanisms controlling grasping function (Nowak et al., 2001; Hermsdörfer et al., 2003). The forces used to grip and lift objects are initially predicted, based on the object's visual properties (Gordon et al., 1991) and the individual's prior experience lifting similar objects (Witney and Wolpert, 2007). Once an object has been gripped, sensory information is used to monitor and regulate the forces during the lift (Johansson and Westling, 1984). These reactive updates are reliant on sensory information pertaining to the task, with cutaneous mechanoreceptors playing a key role in force regulation during grasping and lifting tasks (Johansson and Westling, 1987; Johansson and Flanagan, 2009a). Previous studies have employed grasp-lift-replace paradigms to study deficits in OA anticipatory and reactive control of grasping, but these studies have been limited to assessing unimanual control (Cole, 1991; Danion et al., 2007). Furthermore, studies in healthy ageing and grasping have not accounted for OA samples containing wide-ranging levels of manual dexterity (Desrosiers et al., 1995), leading to inaccurate links being made between research findings and the reduced motor function observed in OA. The use of electromyography (EMG) in grasping studies has also been limited to date (Maier and Hepp-Reymond, 1995), however such analysis could provide new insight into the neural adaptations that underlie the consistently reported behavioural findings of increased grip force, safety margins and slower lifting times seen in OA (Cole, 2009; Diermayr et al., 2011).

This thesis has addressed the short-comings discussed above – experiment one documents the building of a manipulandum system that is capable of assessing the anticipatory and reactive grasping of OA in a bimanual capacity. The system can be used within a lab setting and can be transported to community centres, care homes and to individuals' houses to reach OA who lack the mobility to travel. Experiments two and three focused on the study of anticipatory and reactive grasping control in OA. Experiment two explored well-documented unimanual findings in a bimanual context. Experiment three explored unimanual and bimanual grasping in OA with good and poor levels of manual dexterity. Both experiments two and three used the manipulanda built in experiment one and also employed non-negative matrix factorisation (NMF) to study changes in muscle synergies during the grasping of younger and older adults. This chapter discusses the key findings of the thesis, limitations of the current project, future directions and the impact of the thesis findings.

8.2 Main findings & implications

8.2.1 Developing a portable, bimanual manipulandum system

Experiment one detailed the development and testing of a portable, bimanual manipulandum system, that can be used to assess unimanual and bimanual grasping, whilst adapting internal properties of the manipulanda such as its mass. The manipulanda offer a valid and reliable way to collect grip force and load force data without expensive 6-DoF load cells. This new approach uses an already existing optoelectronic system (Qualisys) but such an approach can also be adapted to use two or more 2D cameras and a reference frame to collect 3D kinematic data (Winter, 2009). This novel approach provides a more portable system to take into the community and care homes which, in turn, improves access to hard to reach groups of OA, who potentially show greater motor decline than OA samples used in lab-based research to date. Portable testing was put into practice during experiments two and three, where a combination of lab-based testing and community centre data collection was used. Data collection in community centres created new challenges but allowed data to be collected on individuals who would have been unlikely to take part if they had to travel to a laboratory setting. Future studies exploring grasping and ageing should consider developing portable testing protocols where possible, to reduce the sampling bias that may be caused when testing takes place solely within a university setting.

8.2.2 Reduced anticipatory control in older adults

Experiments two and three assessed anticipatory control of grasping using a cross-correlation analysis between the change in grip force (ΔGF) and change in load force (ΔLF) during the initial transport phase. This analysis offers an insight into an individual's ability to correctly predict task requirements and accurately scale grip force (GF) and load force (LF) (McDonnell et al., 2006). Cross-correlation analysis has previously found differences in anticipatory grasping control between healthy individuals and clinical populations with sensorimotor loss (Duque et al., 2003; McDonnell et al., 2006), but had not been explored in a grasp-lift-replace task with younger adults (YA) and OA. Experiment two showed there was a significant difference in anticipatory control between YA and OA, with experiment three concluding that a reduced cross-correlation was the key grasping variable that explained differences between older adults with good levels of manual dexterity (OA G) and older adults with poor levels of manual dexterity (OA P). These data indicate OA with reduced manual dexterity (OA P) show a reduced capacity to forward plan and execute anticipatory aspects of grasping.

The potential mechanisms responsible for the reduced anticipatory control seen in OA during grasping are challenging to pinpoint. Anticipatory control is consistently observed in healthy individuals during grasping tasks (Johansson and Westling, 1984; McDonnell et al., 2005; Kimpara et al., 2020). However, the mechanisms responsible for anticipatory GF control are decentralised across the sensorimotor system. Evidence from grasping tasks in healthy YA highlight the importance of visual cues in correctly deploying anticipatory GF control (Gordon et al., 1991; Buckingham et al., 2009), meaning the reduced anticipatory control could be a result of OA being unable to accurately process visual cues about an object's size and weight. Grasping studies with hemiplegia patients have shown a correlation between reduced size of the corticospinal tracts at the level of the cerebral peduncles and anticipatory grip force control (Duque et al., 2003). Such findings indicate OA's reduced anticipatory control may be a result of changes to the corticospinal system that occurs with ageing.

EMG analysis from the anticipatory phase of the lift offers further insight into the motor control mechanisms that may underpin reduced anticipatory control in OA. Findings from experiment two (chapter 6) demonstrate YA are able to selectively recruit muscles in the forearm and the abductor pollicis brevis (APB) independently during the initial grasp and transport phase. Whereas, OA show a greater temporal coupling between the activation of muscle synergies in the forearm and APB (figure 6.18). YA display a peak in APB activity, followed by a peak in forearm activity, such independent recruitment was not present in OA. This discovery was expanded in experiment three (chapter 7) where OA were sub-grouped into groups with good (OA G) and poor (OA P) levels of manual dexterity. During the grasping and transport phases of the lift the selective activation of forearm muscles and APB were diminished as we move from YA to OA G, then further reduce between OA G and OA P (figure 7.16). These findings coincide with the time-point where OA G and OA P show a significant reduction in their ability to scale GF to changes in LF. Based on this evidence, older adults' reduced anticipatory control may be caused by a reduced ability to selectively activate distal muscles in the upper limb during the initial grasp and lifting phase (Maier and Hepp-Reymond, 1995; Hoozemans and Van Dieën, 2005). The corticospinal tract is the dominant pathway controlling muscles located in the forearm and hand (Lemon et al., 1995), consequently, the changes in muscular control seen in OA during the anticipatory timeframe provides evidence that changes to the corticospinal system might be responsible for OA who present with reduced anticipatory control.

This thesis concludes that OA maintain the ability to produce an anticipatory response during grasping, but the precision of their anticipatory response, represented by the cross-correlation coefficient between GF and LF, is reduced compared to YA. Such findings have been speculated before (Danion et al., 2007), but a subsequent review of the literature had indicated limited evidence supporting such claims (Diermayr et al., 2011). Targeting the precise mechanisms behind reduced anticipatory control in OA falls outside the scope of this thesis. However, by synthesising findings from experiments two and three with previous research we can focus on where these changes may reside. Figure 8.1 highlights a simple schematic sequence of anticipatory control: forward planning (cortical & subcortical) -> muscular control (EMG) -> measured behaviour (kinetics and kinematics) (Wolpert, 2007). The current thesis and work by Kanekar and Aruin (2014) have demonstrated changes in the measured behaviour (figure 7.13a) and muscular control during anticipatory control (figure 7.16 & table 7.1), nevertheless there are still three potential scenarios that may explain the cause of reduced anticipatory control in OA – (A) Both forward planning and muscular control are affected as a function of age, leading to a change in behaviour. (B) Forward planning ability is still in tact, but muscular control is diminished in OA; leading to an observed change in muscular control and behaviour during anticipatory stages of grasping. (C) Forward planning is dimished in OA and this is reflected in muscular control and behaviour, despite no degredation in the subsequent phases of muscular control and behaviour. Where these anticipatory deficits reside is a question for future research.

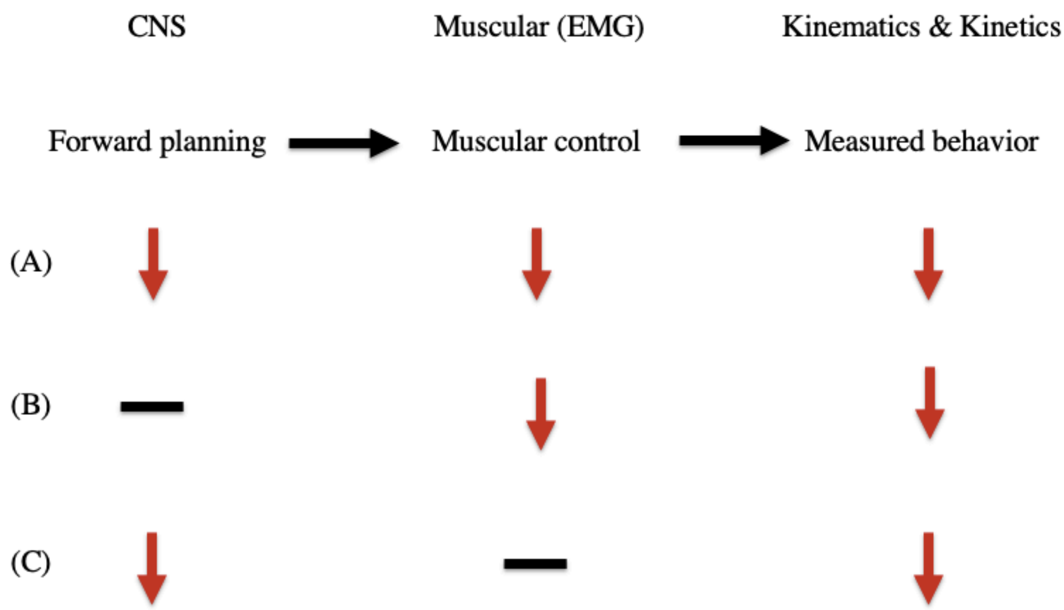


Figure 8.1: A schematic diagram of anticipatory control – forward planning > muscular control > measured behaviour. The three rows beneath highlight potential changes in the motor system of OA. The red arrows indicate a reduction in that phase, the black dashes represent no change in the system compared to YA. Please refer to figure 7.16 & table 7.1 for evidence of changes in muscular control and figure 7.13a for evidence of changes in kinetics in OA during the anticipatory phase on grasping.

The findings of this thesis build on previous studies indicating anticipatory control is affected by age (Danion et al., 2007; Kanekar and Aruin, 2014) by demonstrating such effects are present in unimanual and bimanual grasp-lift-replace tasks. Experiment three extends this area of research demonstrating anticipatory control separates OA with good from OA with poor levels of manual dexterity.

8.2.3 Reactive grasping control in older adults

Once an object has been grasped sensory information is used to update the GF and LF used to grip and transport the object – this is known as the reactive phase of grasping (Nowak and Hermsdörfer, 2006). Such reactive responses are visible with latencies as short as ~75ms (Johansson and Westling, 1987) but continue throughout the lift once initial reactive updates are made (Johansson and Westling, 1984). Experiment two highlights that during reactive phases of grasping (the stable phase where there we no unexpected changes to the task) OA use increased levels of GF and hold objects with a larger safety margin. They also hold objects more stable than YA, potentially to limit the need to update grip force in a reactive manner, as previous studies have shown OA struggle to detect and react to small changes in LF during grasping (Cole and Rotella, 2001). Experiment three found changes in anticipatory control between OA G and OA P but no significant differences in reactive control between OA G and OA P, which suggests anticipatory changes in grasping are more associated with declines in manual dexterity observed in OA. However, this should not be taken as a definitive conclusion – instead these findings reflect the grasp-lift-replace paradigm's capability for detecting anticipatory changes but restricted ability to quantify reactive control.

During the initial stages of grasping (anticipatory control) there are clear changes in GF and LF signals for YA (Johansson and Westling, 1984) and OA (Cole, 1991). Cross-correlation analysis during this temporal window offers an in-depth insight in how these signals are co-varying (Duque et al., 2003; McDonnell et al., 2005). However, a similar analysis is not possible during the stable (reactive) phase of the lift. During the stable phase there are minimal changes in amplitude to GF and LF signals (Johansson and Westling, 1984). Cross-correlation analysis during this temporal window cannot detect changes in the GF and LF above random noise residing in the signal (Winter, 2009). Consequently, researchers should focus on adapting the grasp-lift-replace paradigm to better understand reactive control in OA. Future research in ageing should consider using concepts from the size-weight illusion (Buckingham et al., 2016) or adding unexpected permutations (Danion et al., 2007) during the stable phase to better explore reactive control in OA, as both will require reactive updates in force scaling based on sensory feedback.

8.2.4 Slowing of movements in older adults

The reach-grasp-lift-replace action can be broken down into smaller sections, each with a sub-goal. Such phases and sub-goals include the: reaching phase – transporting the arm, pre-loading phase – creating a secure contact with the object, transport phase – safely lifting the object (Flanagan et al., 2009). These sub-goals rely on different sensory contributions, with vision playing a key role in transporting the limbs (Johansson et al., 2001), before mechanoreceptors begin to provide essential information about fingertip pressure as the object is contacted (Westling and Johansson, 1987). OA specifically showed slowing during the loading phase of the task; for both unimanual and bimanual conditions. The loading phase marks a timepoint where the motor system will make a downregulation in the use of visual feedback and shift towards the use of cutaneous feedback (Johansson and Flanagan, 2009b). Both OA groups (OA G and OA P) showed a significant reduction in cutaneous sensitivity (See section 7.3.4, Semmes-Weinstein scores) potentially explaining why OA struggle with this transition and take longer to initiate the transport phase. The fact that loading time and Semmes-Weinstein scores did not significantly differ between OA G and OA P in experiment three (section 7.34) suggests the slowing of movements seen in OA is a learned behaviour, potentially to cope with reduced tactile sensibility, but does not explain reduced manual dexterity seen between OA G and OA P.

8.2.5 Bimanual control of grasping

Despite researchers suggesting the need for more bimanual research in ageing over a decade ago (Cole, 2009), little research has been carried out specifically using grasp-lift-replace paradigms in OA (for a meta-analysis of wider bimanual research in ageing see Krehbiel et al. (2017)). Previous unimanual grasp-lift-replace studies have shown OA display slower lifting times, increases in peak GF, grip force to load force ratios (GF:LF) and safety margins during grasp-lift-replace tasks (Cole, 2009). Data from experiment two show these commonly seen characteristics in OA unimanual grasping (increased GF, GF:LF and safety margins) are also present in bimanual grasping. Interestingly, experiment two shows both YA and OA make similar adjustments when moving from unimanual to bimanual tasks. Both YA and OA exhibited slower lifting times (figures 6.2b), reduced peak load force (figure 6.9a) and increased GF:LF (figure 6.11b) as they transition to bimanual conditions – indicating a slower, more cautious grasping strategy. Experiment three found all three groups (YA, OA G, OA P) make similar adjustments when transitioning from unimanual to bimanual tasks, suggesting similar adaptations are still used for bimanual grasping irrespective of OA presenting with high (OA G) or low (OA P) levels of manual dexterity.

Previous bimanual grasping research with YA has found anticipatory force scaling is similar to that seen in unimanual tasks (Diedrichsen et al., 2005; Witney and Wolpert, 2007). Findings from this thesis support this view, with minimal adaptations evident in YA anticipatory force control between the unimanual and bimanual conditions. Experiments two and three also indicate that the reduced anticipatory force control seen in OA is consistent across unimanual and bimanual conditions (figure 7.13a). There is already a strong body of evidence documenting OA reduced bimanual function (Krehbiel et al., 2017). This thesis adds reduced anticipatory force scaling to this list of bimanual adaptations observed between YA and OA. However, findings from this thesis indicate that the reduced anticipatory force scaling observed in OA compared to YA is consistent across unimanual and bimanual conditions; not exaggerated in bimanual conditions.

8.3 Wider considerations of age & motor control

Chapters one and two detail the multifaceted changes that occur within the sensorimotor system as a function of age. Sensorimotor adaptations are often viewed as the root cause for any changes in motor performance that occur within OA (Cole, 2009; Diermayr et al., 2011). However, ageing creates changes across the CNS, affecting not only motor control but wider aspects of cognition and memory. Motor control research exploring the links between cognition, memory and motor performance is still in its infancy (Carment et al., 2018), but based on previous research, it is clear that tasks such as grasping, reaching and lifting objects require aspects of decision making and memory (Cole et al., 1999; Cole and Rotella, 2002). For example, planning up-coming lifts based on previous experiences of lifting similar looking objects (Gordon et al., 1991). Cognition and memory are not commonly measured within motor control research and were not the focus of this thesis. However, it could be hypothesised that OA's cognitive decline may, in part, be responsible for the changes in anticipatory control, based on the requirement to recall previous task experience and plan the upcoming movement.

The relationship between grasping performance in OA and cognition should be an area explored in future research.

8.4 Thesis limitations

Chapter four documents the development of the manipulandum system used throughout this thesis. This tool provided a valid and reliable way of collecting data over the subsequent three years of data collection. There were two limitations of the current tool that could not be overcome within the constraints of the project. Previous research has shown OA create increased tangential forces compared to YA, when applying a perpendicular force into a surface during force tracing tasks (Cole, 2006). These increased, non-perpendicular forces may increase un-wanted torque placed upon an object, causing the object to slip or twist (Cole, 2009). The current manipulanda contained uniaxial load cells meaning non-perpendicular forces could not be measured. A second limitation of the manipulanda developed were their inability to separate pre-loading from loading phases during the initial contact of the lift. Using acceleration data and the objects' mass to calculate load force means the precise load force is unknown until the manipulanda are lifted (pre-lift load force is known to be < object mass * gravity). The consequence was analysis of variables, requiring both GF and LF, began at the start of the transport phase rather than at the loading phase (figure 2.1). Interestingly, this approach found elevated force profiles similar to previous research in ageing (Cole, 1991) and cross-correlation coefficients similar to previous literature in healthy adults that had used loading as the start point for analysis (McDonnell et al., 2005).

Experiment three used the Purdue Pegboard test as a measure of manual dexterity and to sub-group OA into samples with 'good' and 'poor' levels of manual dexterity. Using this paradigm to understand age-related decline in manual dexterity and potential links to ADL could be debated, as the Purdue Pegboard test is not an exact representation of finger movements used during ADL (Gonzalez et al., 2017). However, previous ageing and grasping research has not considered the heterogeneous levels of manual dexterity within the OA population (Cole, 1991; Cole and Beck, 1994; Lowe, 2001; Gilles and Wing, 2003; Parikh and Cole, 2012). Consequently, using the Purdue Pegboard to sub-group OA was deemed a progressive approach and more useful than using age boundaries, such as 50s, 60s, 70s. As previous data indicates these age boundaries show considerable overlap in manual dexterity scores

(Desrosiers et al., 1995). The following section considers how the approach taken in this thesis can be further developed.

8.5 Future directions

Future research should consider combining Purdue Pegboard, Semmes-Weinstein and grip strength testing with questionnaires assessing individuals' ability to perform ADL. Self-reporting clinical questionnaires such as the DASH (disabilities of the arm, shoulder and hand) provide a useful analysis of ADL (Hudak et al., 1996), but have seen little use in healthy ageing and grasping research. Combining the measures above would allow sensorimotor profiles to be created for OA. Sub-grouping OA based on these profiles would give a better understanding of how anticipatory and reactive control of grasping relate to OA who struggle with ADL.

As previously discussed, the grasp-lift-replace paradigm provides great insight into anticipatory control mechanisms, but without adaptation has less sensitivity in detecting changes in reactive control. By adding unexpected permutations (Danion et al., 2007) during the stable phase researchers could better explore reactive updates in force control during unimanual and bimanual grasping. Research to date in unimanual grasping indicates OA show similar latencies to YA in updating GF in a reactive capacity (~80ms), but respond with greater GF levels (Cole and Rotella, 2001). Future research should explore these findings in a bimanual context. The bimanual elements explored in this thesis focused on congruent bimanual tasks, with both manipulanda weighing the same, and the action being temporally synchronised (Ivry et al., 2004). ADL such as cutting food with a knife and fork, or tying shoelaces require the hands to perform differing motions in an asynchronous capacity, therefore future research should ascertain if the anticipatory and reactive findings from this thesis are consistent when performing incongruent bimanual actions – such findings would strengthen links between the findings from this thesis and actions used to perform ADL.

The use of NMF analysis during this thesis provides a useful insight into the coordination of muscles activity in YA and OA during the initial stages of grasping (figures 6.17, 6.18, 7.15, 7.16) and during the stable phase (figures 6.19, 6.20, 7.17, 7.18), however this analysis was limited to four muscles per arm. There are 39 muscles present within the forearm and hand relating to grip (Maier and Hepp-Reymond, 1995), and wider muscle groups in the upper arm and shoulder that are responsible for transporting and stabilising the upper limb (D'Avella et al., 2006). The inherent challenges that are present when collecting surface EMG data, such as locating small distal muscles and potential cross-talk between muscles (Hug, 2011) make collecting data from all of these muscles near impossible. However, future research should extend the findings from this thesis with EMG analysis that includes more muscles in the hand, forearm and upper arm. This will provide a richer picture of the muscle synergies that are used during grasping by YA and OA.

The manipulanda used throughout this thesis provide a valid and reliable way of capturing GF and LF, with the ability to measure grasping inside the lab and be transported outside of the lab to community centres and care homes. However, this approach is still reliant on additional cameras to capture the manipulandum's acceleration (optoelectronic systems or multiple video cameras). Future research should continue to make manipulandum systems more portable to help reach individuals with reduced mobility. The use of an in-built accelerometer to measure LF was unsuccessful in experiment one (table 4.2), but adding a gyroscope to future builds might help correct error present within accelerometer data (Winter, 2009) and allow GF and LF to be collected with no need for additional camera systems.

8.6 Application of findings to healthy ageing & ADL

Ageing causes a multitude of neural and physiological changes (Carmeli et al., 2003b; Clark and Taylor, 2012), resulting in diminished levels of manual dexterity (Desrosiers et al., 1995) and a reduced capacity to perform ADL (Age UK, 2019). There are no simple solutions to overcome these adaptations, however, this thesis sheds light on inhibited anticipatory control as a key factor separating OA with high and low levels of manual dexterity. This section concludes the thesis with how findings can be applied to help OA perform ADL and maintain their independence for longer.

Environmental design plays an integral role in helping OA stay independent – with previous research highlighting how OA struggle to grasp wide objects and can drop wide objects when combined with slippery contact surfaces (Holt et al., 2013). This thesis has identified OA with poor levels of manual dexterity struggle to anticipate and scale GF to changing levels of LF during unimanual and bimanual tasks. Consequently, objects that need to be grasped, lifted and manipulated by OA should cater accordingly. Creating contact surfaces that are coarse and/or tacky increases the coefficient of friction between digits and object (Kinoshita, 1996) allowing the object to be held with a lower grip force. Similarly, creating cups and glasses with an increasing taper, rather than straight edges reduces the GF:LF needed to ensure a secure grasp (Wing and Lederman, 2009). Both these simple design adaptations afford OA situations where scaling GF to LF can be less precise without an object being dropped. A more nuanced problem is considering how best to help OA correctly predict the levels of GF needed to grasp and lift an object. Data from size-weight illusion studies (Buckingham, 2014) suggests the visual properties of objects should be indicative of their mass to help OA use appropriate levels of GF during the initial stages of the lift – size, material and shape can all affect the explicit understanding of how heavy an object is (Buckingham, 2014). This could support OA in making an appropriate plan for the up-coming task but may not fully resolve the issue of diminished anticipatory control. As figure 8.1 highlights, reduced anticipatory control in OA could be the consequence of i) a diminished ability to plan tasks, ii) a reduced ability to coordinate an appropriate muscle response, or iii) both of the above. Changing the physical appearance of objects should alter an individual's explicit estimation of heaviness (Trewartha and Flanagan, 2016), but may not improve the subsequent motor action performed by that individual.

Making design alterations within the homes of OA will not entirely solve the wider issues associated with independent living. Reaching and grasping items at the supermarket, opening product packaging and safely navigating around a local community are also challenging situations that require dextrous action (Pericu, 2017). A more complete solution would be to slow down or reverse the decline of anticipatory control in OA. This thesis has highlighted the varying levels of anticipatory control present within OA but has not found a conclusive answer as to why this variability exists – only that chronological age is not an ideal predictor. Increased physical activity in OA is well known to improve cardiovascular health and reduce the loss of muscle mass (Taylor et al., 2004) but less is known about how physical activity affects motor control in OA (Seidler et al., 2010). A future area for exploration is understanding if physical activity might mitigate the decline in anticipatory control and help OA stay independent for longer.

8.7 Conclusion

This chapter has summarised findings from experiments one, two and three, considered future directions for research and considered the application of thesis findings for healthy ageing and performing ADL. In summary, reduced anticipatory grasping control is associated with OA, and is further reduced in OA who show lower levels of manual dexterity. All OA show slower, more cautious grasping strategies compared to YA, but this is not indicative of reduced manual dexterity within OA. Instead, the slower grasping and lifting strategies observed in OA are potentially a learned behaviour to cope with reduced tactile sensibility. Reduced anticipatory control and slower grasping strategies in OA appear consistent across unimanual and bimanual grasp-lift-replace tasks. Based on these findings simple changes can be made to OA environments to help them perform ADL. Introducing coarse and/or tacky contact points and creating objects with tapered edges will reduce the need for precise force scaling and prevent objects from being dropped. Future research should explore if interventions, such as increased levels of physical activity, can slow the decline of anticipatory grasping control observed in OA.

List of References

Age UK 2019. Briefing: Health and care of older people in England.pp.1–68.

Alnaqeeb, M.A. and Goldspink, G. 1987. Changes in fibre type, number and diameter in developing and ageing skeletal muscle. Journal of anatomy. 153,pp.31–45.

Augurelle, A.-S., Smith, A.M., Lejeune, T. and Thonnard, J.-L. 2003. Importance of cutaneous feedback in maintaining a secure grip during manipulation of hand-held objects. Journal of neurophysiology. 89(2),pp.665–671.

Benjuya, N., Melzer, I. and Kaplanski, J. 2004. Aging-induced shifts from a reliance on sensory Input to muscle cocontraction during balanced standing. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 59(2),pp.166–171.

Bizzi, E., Mussa-Ivaldi, F.A. and Giszter, S. 1991. Computations underlying the production of movement: a biological persective. Science. 253 (July),pp.287–291.

Blennerhassett, J.M., Matyas, T.A. and Carey, L.M. 2007. Impaired discrimination of surface friction contributes to pinch grip deficit after stroke. Neurorehabilitation and Neural Repair. 21(3),pp.263–272.

Bleyenheuft, Y. and Gordon, A.M. 2014. Precision grip in congenital and acquired hemiparesis: Similarities in impairments and implications for neurorehabilitation. Frontiers in Human Neuroscience. 8 (June),pp.1–11.

Bleyenheuft, Y. and Thonnard, J.-L. 2010. Predictive and reactive control of precision grip in children with congenital hemiplegia. Neurorehabilitation and neural repair. 24(4),pp.318–327.

Bourbonnais, D., Frak, V., Pilon, J.-F. and Goyette, M. 2008. An instrumented cylinder measuring pinch force and orientation. Journal of neuroengineering and rehabilitation. 5,pp.2-11

Bracewell, R.M., Wing, A.M., Soper, H.M. and Clark, K.G. 2003. Predictive and reactive co-ordination of grip and load forces in bimanual lifting in man. European Journal of Neuroscience. 18(8),pp.2396–2402.

Brochier, T., Spinks, R., Umilta, M. and Lemon, R. 2009. Recording of electromyogram activity in the money during skilled grasping In: D. A. Nowak and J. Hermsdörfer, eds. Sensorimotor Control of grasping: Physiology and Pathophysiology. Cambridge: Cambridge University Press, pp. 61–71.

Brunet, J.P., Tamayo, P., Golub, T.R. and Mesirov, J.P. 2004. Metagenes and molecular pattern discovery using matrix factorization. Proceedings of the National Academy of Sciences of the United States of America. 101(12),pp.4164–4169.

Buckingham, G. 2014. Getting a grip on heaviness perception: A review of weight illusions and their probable causes. Experimental Brain Research. 232(6),pp.1623–1629.

Buckingham, G., Cant, J.S. and Goodale, M.A. 2009. Living in a material world: How visual cues to material properties affect the way that we lift objects and perceive their weight. Journal of Neurophysiology. 102(6),pp.3111–3118.

Buckingham, G. and Goodale, M.A. 2010. Lifting without seeing: The role of vision in perceiving and acting upon the size weight Illusion. PLoS ONE. 5(3).

Buckingham, G., Michelakakis, E.E. and Cole, J. 2016. Perceiving and acting upon weight illusions in the absence of somatosensory information. Journal of Neurophysiology. 115(4),pp.1946–1953.

Calabro, F.J. and Perez, M.A. 2016. Bilateral reach-to-grasp movement asymmetries after human spinal cord injury. Journal of neurophysiology. 115(1),pp.157–167.

Carmeli, E., Patish, H. and Coleman, R. 2003a. The aging hand. The journals of gerontology. Series A, Biological sciences and medical sciences. 58(2),pp.146–152.

Carmeli, E., Patish, H. and Coleman, R. 2003b. The aging hand. Journal of Gerontology. 58(2),pp.146–152.

Carment, L., Abdellatif, A., Lafuente-Lafuente, C., Pariel, S., Maier, M.A., Belmin, J. and Lindberg, P.G. 2018. Manual dexterity and aging: A pilot study disentangling sensorimotor from cognitive decline. Frontiers in Neurology. 9(OCT),pp.1–11.

Cashaback, J.G.A., McGregor, H.R., Pun, H.C.H., Buckingham, G. and Gribble, P.L. 2017. Does the sensorimotor system minimize prediction error or select the most likely prediction during object lifting? Journal of Neurophysiology. 117(1),pp.260–274.

Clark, B. and Taylor, J. 2012. Age-Related Changes in Motor Cortical Properties and Voluntary Activation of Skeletal Muscle. Current Aging Science. 4(3),pp.192–199.

Coats, R.O. and Wann, J.P. 2012. Reaching a Better Understanding of the Control of Bimanual Movements in Older Adults. PLoS ONE. 7(10).

Coats, R.O., Wilson, A.D., Snapp-Childs, W., Fath, A.J. and Bingham, G.P. 2014. The 50s cliff: Perceptuo-motor learning rates across the lifespan. PLoS ONE. 9(1).

Cole, K.J. 2006. Age-related directional bias of fingertip force. Experimental Brain Research. 175(2),pp.285–291.

Cole, K.J. 1991. Grasp force control in older adults. Journal of Motor Behavior. 23(4),pp.251–258.

Cole, K.J. 2009. The effects of aging on sensorimotor control of the hand. In Sensorimotor Control of Grasping.

Cole, K.J. and Abbs, J.H. 1988. Grip force adjustments evoked by load force perturbations of a grasped object. Journal of Neurophysiology. 60(4),pp.1513–1522.

Cole, K.J. and Beck, C.L. 1994. The stability of precision grip force in older adults. Journal of Motor Behavior. 26(2),pp.171–177.

Cole, K.J. and Rotella, D.L. 2001. Old age affects fingertip forces when restraining an unpredictably loaded object. Experimental Brain Research. 137(1),pp.535–542.

Cole, K.J. and Rotella, D.L. 2002. Old age impairs the use of arbitrary visual cues for predictive control of fingertip forces during grasp. Experimental Brain Research. 143(1),pp.35–41.

Cole, K.J., Rotella, D.L. and Harper, J.G. 1999. Mechanisms for age-related changes of fingertip forces during precision gripping and lifting in adults. The Journal of Neuroscience. 19(8),pp.3238–47.

Cole, K.J., Rotella, D.L. and Harper, J.G. 1998. Tactile impairments cannot explain the effect of age on a grasp and lift task. Experimental Brain Research. 121(3),pp.263–269.

D'Avella, A., Portone, A., Fernandez, L. and Lacquaniti, F. 2006. Control of fast-reaching movements by muscle synergy combinations. Journal of Neuroscience. 26(30),pp.7791–7810.

Danion, F., Descoins, M. and Bootsma, R.J. 2007. Aging affects the predictive control of grip force during object manipulation. Experimental brain research. 180(1),pp.123–37.

Davare, M., Andres, M., Clerget, E., Thonnard, J.L. and Olivier, E. 2007. Temporal dissociation between hand shaping and grip force scaling in the anterior intraparietal area. Journal of Neuroscience. 27(15),pp.3974–3980.

Delbono, O. 2003. Neural control of aging skeletal muscle. Aging cell. 2(1),pp.21–29.

Delis, I., Berret, B., Pozzo, T. and Panzeri, S. 2013. Quantitative evaluation of muscle synergy models: A single-trial task decoding approach. Frontiers in Computational Neuroscience. 7 (Feb),pp.1–21.

Delis, I., Panzeri, S., Pozzo, T. and Berret, B. 2014. A unifying model of concurrent spatial and temporal modularity in muscle activity. Journal of Neurophysiology. 111(3),pp.675–693.

Desrosiers, J., Hébert, R., Bravo, G. and Dutil, E. 1995. The purdue pegboard test: Normative data for people aged 60 and Over. Disability and Rehabilitation. 17(5),pp.217–224.

Desrosiers, J., Hébert, R., Bravo, G. and Rochette, A. 1999. Age-related changes in upper extremity performance of elderly people: A longitudinal study. Experimental Gerontology. 34(3),pp.393–405.

Diedrichsen, J., Verstynen, T., Lehman, S.L. and Ivry, R.B. 2005. Cerebellar Involvement in Anticipating the Consequences of Self-Produced Actions During Bimanual Movements. Journal of Neurophysiology. 93(2),pp.801–812.

Diermayr, G., McIsaac, T.L. and Gordon, A.M. 2011. Finger force coordination underlying object manipulation in the elderly - A mini-review. Gerontology. 57(3),pp.217–227.

Dimitriou, P. and Buckingham, G. 2018. Bimanual Lifting: Do Fingertip Forces Work Independently or Interactively? Journal of Motor Behavior. 50(1),pp.26–36.

Duque, J., Thonnard, J.L., Vandermeeren, Y., Sébire, G., Cosnard, G. and Olivier, E. 2003. Correlation between impaired dexterity and corticospinal tract dysgenesis in congenital hemiplegia. Brain. 126(3),pp.732–747.

Ebied, A., Kinney-Lang, E., Spyrou, L. and Escudero, J. 2018. Evaluation of matrix factorisation approaches for muscle synergy extraction. Medical Engineering and Physics. 57 (May),pp.51–60.

Endo, S., Wing, A.M. and Bracewell, R.M. 2009. Two Hands in Object-Orientated Action In: D. Nowak and J. Hermsdörfer, eds. Sensorimotor Control of Grasping. Cambridge: Cambridge University Press, pp. 204–218.

Flanagan, J.R., King, S., Wolpert, D.M. and Johansson, R.S. 2001. Sensorimotor prediction and memory in object manipulation. Canadian journal of experimental. 55(2),pp.87–95.

Flanagan, J.R., Merritt, K. and Johansson, R. 2009. Predictive Mechanisms and Object Representations used in Object Manipulation. In Sensorimotor Control of Grasping (D. A. Nowak & J. Hermsdörfer, eds.). Cambridge: Cambridge Press.

Flanagan, J.R. and Tresilian, J.R. 1994. Grip-Load Force Coupling: A General Control Strategy for Transporting Objects. Journal of Experimental Psychology: Human Perception and Performance. 20(5),pp.944–957.

Flanagan, J.R. and Wing, A.M. 1997. The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. The Journal of neuroscience : the official journal of the Society for Neuroscience. 17(4),pp.1519–28.

Gentner, R. and Classen, J. 2006. Modular Organization of Finger Movements by the Human Central Nervous System. Neuron. 52(4),pp.731–742.

Gescheider, G.A., Bolanowski, S.J., Hall, K.L., Hoffman, K.E. and Verrillo, R.T. 1994. The effects of aging on information-processing channels in the sense of touch: I. Absolute sensitivity. Somatosensory & Motor Research. 11(4),pp.345–357.

Gilles, M.A. and Wing, A.M. 2003. Age-related changes in grip force and dynamics of hand movement. Journal of motor behavior. 35(February),pp.79–85.

Gonzalez, V., Rowson, J. and Yoxall, A. 2017. Analyzing finger interdependencies during the Purdue Pegboard Test and comparative activities of daily living. Journal of Hand Therapy. 30(1),pp.80–88.

Gordon, a M., Forssberg, H. and Iwasaki, N. 1994. Formation and lateralization of internal representations underlying motor commands during precision grip. Neuropsychologia. 32(5),pp.555–68.

Gordon, M., Forssberg, H., Johansson, R.S. and Westling, G. 1991. Visual size cues in the programming of manipulative forces during precision grip. Experimental Brain Research. (83),pp.477–482.

Gorniak, S.L. and Alberts, J.L. 2013. Effects of aging on force coordination in bimanual task performance. Experimental brain research. 229(2),pp.273–84.

Grover, F.M., Nalepka, P., Silva, P.L., Lorenz, T. and Riley, M.A. 2019. Variable and intermittent grip force control in response to differing load force dynamics. Experimental Brain Research. 237(3),pp.687–703.

Hadjiosif, A.M. and Smith, M. a 2015. Flexible Control of Safety Margins for Action Based on Environmental Variability. The Journal of neuroscience : the official journal of the Society for Neuroscience. 35(24),pp.9106–21.

Hartigan, J.A. and Wong, M.A. 1979. Algorithm AS 136 : A K-Means Clustering Algorithm. Journal of the Royal Statistical Society. 28(1),pp.100–108.

Hashemi Oskouei, A., Paulin, M.G. and Carman, A.B. 2013. Intra-session and inter-day reliability of forearm surface EMG during varying hand grip forces. Journal of Electromyography and Kinesiology. 23(1),pp.216–222.

Hepple, R.T. and Rice, C.L. 2016. Innervation and neuromuscular control in ageing skeletal muscle. Journal of Physiology. 594(8),pp.1965–1978.

Hermens, H.J., Freriks, B., Disslhorst_Klug, C. and Rau, G. 2000. Development of recommendations for SEMG sensors and sensor placement procedures. Journal of Electromyography and Kinesology. 10(1),pp.361–374.

Hermsdörfer, J., Elias, Z., Cole, J.D., Quaney, B.M. and Nowak, D.A. 2008. Preserved and impaired aspects of feed-forward grip force control after chronic somatosensory deafferentation. Neurorehabilitation and Neural Repair. 22(4),pp.374–384.

Hermsdörfer, J., Hagl, E., Nowak, D.A. and Marquardt, C. 2003. Grip force control during object manipulation in cerebral stroke. Clinical Neurophysiology. 114(5),pp.915–929.

Hermsdörfer, Joachim 2009. Analysis of grip forces during object manipulation In: D. A. Nowak and J. Hermsdörfer, eds. Sensorimotor Control of grasping: Physiology and Pathophysiology. New York: Cambridge University Press, pp. 3–19.

Holmes, M.W.R., Tat, J. and Keir, P.J. 2015. Neuromechanical control of the forearm muscles during gripping with sudden flexion and extension wrist perturbations. Computer Methods in Biomechanics and Biomedical Engineering. 18(16),pp.1826–1834.

Holt, R.J., Lefevre, A.S., Flatters, I.J., Culmer, P., Wilkie, R.M., Henson, B.W., Bingham, G.P. and Mon-Williams, M. 2013. Grasping the Changes Seen in Older Adults When Reaching for Objects of Varied Texture. PLoS ONE. 8(7),p.e69040.

Hoozemans, M.J.M. and Van Dieën, J.H. 2005. Prediction of handgrip forces using surface EMG of forearm muscles. Journal of Electromyography and Kinesiology. 15(4),pp.358–366.

Hudak, P.L., Amadio, P.C. and Bombardier, C. 1996. Development of an upper extremity outcome measure: the DASH (disabilities of the arm, shoulder and hand) [corrected]. Am J Ind Med 1996 (Sep);30(3),pp.602–208.

Huesler, E.J., Maier, M.A. and Hepp-Reymond, M.C. 2000. EMG activation patterns during force production in precision grip. III. Synchronisation of single motor units. Experimental Brain Research. 134(4),pp.441–455.

Hug, F. 2011. Can muscle coordination be precisely studied by surface electromyography? Journal of Electromyography and Kinesiology. 21(1),pp.1–12.

Hug, F. and Tucker, K. 2017. Surface Electromyography to Study Muscle Coordination. In Müller, B. and Wolf, S. Handbook of Human Motion. Springer,

Hug, F., Turpin, N.A., Guével, A. and Dorel, S. 2010. Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? Journal of Applied Physiology. 108(6),pp.1727–1736.

Ivry, R., Diedrichsen, J., Spencer, R., Hazeline, E. and Semjen, A. 2004. A Cognitive Neuroscience Perspective on Bimanual Coordination and Interference. In Swinnen, S.

And Duysens, J. Neuro-Behavioral Determinants of Interlimb Coordination. Springer US

Iyengar, V., Santos, M.J., Ko, M. and Aruin, A.S. 2009. Grip force control in individuals with multiple sclerosis. Neurorehabil Neural Repair. 23(8),pp.855–861.

Jaber, R., Hewson, D.J. and Duchêne, J. 2012. Design and validation of the Grip-ball for measurement of hand grip strength. Medical engineering & physics. 34(9),pp.1356–1361.

Jenmalm, P. and Johansson, R.S. 1997. Visual and Somatosensory Information about Object Shape Control Manipulative Fingertip Forces. The Journal of Neuroscience. 17(11),pp.4486–4499.

Jenmalm, P., Schmitz, C., Forssberg, H. and Ehrsson, H.H. 2006. Lighter or heavier than predicted: Neural correlates of corrective mechanisms during erroneously programmed lifts. Journal of Neuroscience. 26(35),pp.9015–9021.

Johanson, M.E., Valero-Cuevas, F.J. and Hentz, V.R. 2001. Activation patterns of the thumb muscles during stable and unstable pinch tasks. Journal of Hand Surgery. 26(4),pp.698–705.

Johansson, R. and Westling, G. 1987. Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip. Experimental Brain Research. 66(1),pp.141–154.

Johansson, R., Westling, G., Backstorm, A. and Flanagan, J.R. 2001. Eye – Hand Coordination in Object Manipulation. The Journal of Neuroscience. 21(17),pp.6917–6932.

Johansson, R.S. and Flanagan, J.R. 2009a. Coding and use of tactile signals from the fingertips in object manipulation tasks. Nature Reviews Neuroscience. 10(5),pp.345–359.

Johansson, R.S. and Flanagan, J.R. 2009b. Sensory Control of Object Manipulation In: D. A. Nowak and J. Hermsdörfer, eds. Sensorimotor Control of Grasping. Cambridge: Cambridge University Press, pp. 141–160.

Johansson, R.S. and Westling, G. 1984. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. Experimental brain research. 56(3),pp.550–564.

Johansson, R.S. and Westling, G. 1987. Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip. ,pp.141–154.

Kanekar, N. and Aruin, A.S. 2014. The effect of aging on anticipatory postural control. Experimental Brain Research. 232(4),pp.1127–1136.

Kang, H. and Dingwell, J. 2009. Dynamics and stability of muscle activations during walking in healthy young and older adults. Journal of Biomechanics. 42(14),pp.2231–2237.

Kang, N. and Cauraugh, J.H. 2014. Bimanual Force Variability and Chronic Stroke: Asymmetrical Hand Control. PLoS ONE. 9(7),p.e101817.

Keenan, K.G., Massey, W. V., Walters, T.J. and Collins, J.D. 2012. Sensitivity of EMG-EMG coherence to detect the common oscillatory drive to hand muscles in young and older adults. Journal of Neurophysiology. 107(10),pp.2866–2875.

Kimpara, H., Mbanisi, K.C., Li, Z., Troy, K.L., Prokhorov, D. and Gennert, M.A. 2020. Force Anticipation and Its Potential Implications on Feedforward and Feedback Human Motor Control. Human Factors.

Kinoshita, H. 1996. A comparison of prehension force control in young and elderly individuals. European Journal of Applied Physiology and Occupational Physiology. 74(5),pp.450–460.

Koo, T.K. and Li, M.Y. 2016. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. Journal of Chiropractic Medicine. 15(2),pp.155–163.

Krehbiel, L.M., Kang, N. and Cauraugh, J.H. 2017. Age-related differences in bimanual movements: A systematic review and meta-analysis. Experimental Gerontology. 98 (July),pp.199–206.

Lang, C. and Schieber, M. 2009. Stroke In: D. A. Nowak and J. Hermsdörfer, eds. Sensorimotor Control of Grasping. Cambridge: Cambridge University Press, pp. 296–310.

Lemon, R.N., Johansson, R.S. and Westling, G. 1995. Corticospinal control during reach, grasp, and precision lift in man. Journal of Neuroscience. 15(9),pp.6145–6156.

Lin, C.-H., Chou, L.-W., Wei, S.-H., Lieu, F.-K., Chiang, S.-L. and Sung, W.-H. 2014. Influence of aging on bimanual coordination control. Experimental gerontology. 53,pp.40–7.

Lin, C., Chou, L.W., Wei, S.H., Lieu, F.K., Chiang, S.L. and Sung, W.H. 2014. Validity and reliability of a novel device for bilateral upper extremity functional measurements. Computer Methods and Programs in Biomedicine. 114(3),pp.315–323.

Lodha, N., Patten, C., Coombes, S.A. and Cauraugh, J.H. 2012. Bimanual force control strategies in chronic stroke: Finger extension versus power grip. Neuropsychologia. 50(11),pp.2536–2545.

Lowe, B.D. 2001. Precision Grip Force Control of Older and Younger Adults , Revisited. Journal of Occupational Rehabilitation . 11(4),pp.267–280.

Macaluso, A., Nimmo, M.A., Foster, J.E., Cockburn, M., McMillan, N.C. and De Vito, G. 2002. Contractile muscle volume and agonist-antagonist coactivation account for differences in torque between young and older women. Muscle and Nerve. 25(6),pp.858–

863.

Macefield, V.G., Häger-Ross, C. and Johansson, R.S. 1996. Control of grip force during restraint of an object held between finger and thumb: Responses of cutaneous afferents from the digits. Experimental Brain Research. 108(1),pp.155–171.

Maier, M.A. and Hepp-Reymond, M.C. 1995. EMG activation patterns during force production in precision grip - I. Contribution of 15 finger muscles to isometric force. Experimental Brain Research. 103(1),pp.108–122.

Marmon, A.R., Pascoe, M.A., Schwartz, R.S. and Enoka, R.M. 2011. Associations among strength, steadiness, and hand function across the adult life span. Medicine and Science in Sports and Exercise. 43(4),pp.560–567.

Martin, J.A., Ramsay, J., Hughes, C., Peters, D.M. and Edwards, M.G. 2015. Age and grip strength predict hand dexterity in adults. PLoS ONE. 10(2),pp.1–18.

McDonnell, M.N., Hillier, S.L., Ridding, M.C. and Miles, T.S. 2006. Impairments in precision grip correlate with functional measures in adult hemiplegia. Clinical Neurophysiology. 117(7),pp.1474–1480.

McDonnell, M.N., Ridding, M.C., Flavel, S.C. and Miles, T.S. 2005. Effect of human grip strategy on force control in precision tasks. Experimental Brain Research. 161(3),pp.368–373.

Miall, R.C. and Wolpert, D.M. 1996. Forward Models for Physiological Motor Control. Neural Networks. 9(8),pp.1265–1279.

Monzée, J., Lamarre, Y. and Smith, A.M. 2003. The effects of digital anaesthesia on force control using a precision grip. Journal of neurophysiology. 89(2),pp.672–683.

Murata, J., Murata, S., Hiroshige, J., Ohtao, H., Horie, J. and Kai, Y. 2010. The influence of age-related changes in tactile sensibility and muscular strength on hand function in older adult females. International Journal of Gerontology. 4(4),pp.180–183.

Nowak, D. a. and Hermsdörfer, J. 2003. Selective deficits of grip force control during object manipulation in patients with reduced sensibility of the grasping digits. Neuroscience Research. 47,pp.65–72.

Nowak, D.A., Glasauer, S. and Hermsdörfer, J. 2013. Force control in object manipulation-A model for the study of sensorimotor control strategies. Neuroscience and Biobehavioral Reviews. 37(8),pp.1578–1586.

Nowak, D.A. and Hermsdörfer, J. 2006. Predictive and reactive control of grasping forces: On the role of the basal ganglia and sensory feedback. Experimental Brain Research.

173(4),pp.650–660.

Nowak, D.A., Hermsdörfer, J., Glasauer, S., Philipp, J., Meyer, L. and Mai, N. 2001. The effects of digital anaesthesia on predictive grip force adjustments during vertical movements of a grasped object. European Journal of Neuroscience. 14(4),pp.756–762.

Office for National Statistics UK. 2019. United Kingdom population mid-year estimate - Office for National Statistics. Office for National Statistic. (June 2019),pp.1–19.

Parikh, P.J. and Cole, K.J. 2012. Handling objects in old age: forces and moments acting on the object. Journal of Applied Physiology. 112(7),pp.1095–1104.

Paulignan, Y., MacKenzie, C., Marteniuk, R. and Jeannerod, M. 1991. Selective perturbation of visual input during prehension movements - 1. The effects of changing object position. Experimental Brain Research. 83(3),pp.502–512.

Pericu, S. 2017. Designing for an ageing society: products and services. The Design Journal. 20 (sup1),pp.2178–2189.

Platz, T., van Wijck, F., di Bella, P., Johnson, G., Pinkowski, C. and Kim, I.-H. 2005. Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: a multicentre study. Clinical Rehabilitation. 19(4),pp.404–411.

Van Polanen, V. and Davare, M. 2015. Sensorimotor Memory Biases Weight Perception During Object Lifting. Frontiers in human neuroscience. 9 (December).

Portney, L. 2020. Foundations of Clinical Research: Applications to Evidence-Based Practice 4th ed. Philadelphia: F. A. Davis Company.

Poston, B., Santos, A.D. Dos, Jesunathadas, M., Hamm, T.M. and Santello, M. 2010. Force-independent distribution of correlated neural inputs to hand muscles during three-digit grasping. Journal of Neurophysiology. 104(2),pp.1141–1154.

Prevete, R., Donnarumma, F., D'Avella, A. and Pezzulo, G. 2018. Evidence for sparse synergies in grasping actions. Scientific Reports. 8(1),pp.1–16.

Raghavan, P., Krakauer, J.W. and Gordon, A.M. 2006. Impaired anticipatory control of fingertip forces in patients with a pure motor or sensorimotor lacunar syndrome. Brain. 129(6),pp.1415–1425.

Roe, G., Shaw, W.J., Darrall-jones, J. and Phibbs, P. 2018. Reliability and Validity of a Medicine Ball-Contained Accelerometer for Measuring Upper-Body Neuromuscular Performance. The Journal of Strength and Conditioning Research. 32 (January),pp.1–4.

Santello, M., Baud-Bovy, G. and Jörntell, H. 2013. Neural bases of hand synergies. Frontiers in Computational Neuroscience. 7 (April),pp.1–15.

Santello, M., Flanders, M. and Soechting, J.F. 1998. Postural hand synergies for tool use. Journal of Neuroscience. 18(23),pp.10105–10115.

Santos, A.D. Dos, Poston, B., Jesunathadas, M., Bobich, L.R., Hamm, T.M. and Santello, M. 2010. Influence of fatigue on hand muscle coordination and EMG-EMG coherence during three-digit grasping. Journal of Neurophysiology. 104(6),pp.3576–3587.

Seidler, R.D., Bernard, J.A., Burutolu, T.B., Fling, B.W., Gordon, M.T., Gwin, J.T., Kwak, Y. and Lipps, D.B. 2010. Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. Neuroscience and Biobehavioral Reviews. 34(5),pp.721–733.

Shechtman, O., Gestewitz, L. and Kimble, C. 2005. Reliability and validity of the DynEx dynamometer. Journal of Hand Therapy. 18(3),pp.339–347.

Smith, C.D., Umberger, G.H., Manning, E.L., Slevin, J.T., Wekstein, D.R., Schmitt, F.A., Markesbery, W.R., Zhang, Z., Gerhardt, G.A., Kryscio, R.J. and Gash, D.M. 1999. Critical decline in fine motor hand movements in human aging. Neurology. 53(7),pp.1458–1458.

Tanaka, H., Ishikawa, T. and Kakei, S. 2019. Neural Evidence of the Cerebellum as a State Predictor. Cerebellum.

Taylor, A.H., Cable, N.T., Faulkner, G., Hillsdon, M., Narici, M. and Van der Bij, A.K. 2004. Physical activity and older adults: A review of health benefits and the effectiveness of interventions. Journal of Sports Sciences. 22(8),pp.703–725.

Trewartha, K.M. and Flanagan, J.R. 2016. Distinct contributions of explicit and implicit memory processes to weight prediction when lifting objects and judging their weights: an aging study. Journal of Neurophysiology. 116(3),pp.1128–1136.

Turvey, M.T. 1990. Coordination. Am Psychol. 45(8),pp.938–953.

Venkadesan, M. and Valero-Cuevas, F.J. 2008. Neural control of motion-to-force transitions with the fingertip. Journal of Neuroscience. 28(6),pp.1366–1373.

Vermillion, B.C., Lum, P.S. and Lee, S.W. 2015. Proximal arm kinematics affect grip force-load force coordination. Journal of Neurophysiology. 114(4),pp.2265–2277.

Vieluf, S., Godde, B., Reuter, E.-M., Temprado, J.-J. and Voelcker-Rehage, C. 2015. Practice Effects in Bimanual Force Control: Does Age Matter? Journal of Motor Behavior. 47(1),pp.57–72.

Vollmer, B. and Forssberg, H. 2009. Development of grasping and object manipulation In: D.

A. Nowak and J. Hermsdörfer, eds. Sensorimotor Control of Grasping. Cambridge University Press, pp. 235–249.

Warabi, T., Noda, H. and Kato, T. 1986. Effect of aging on sensorimotor functions of eye and hand movements. Experimental Neurology. 92(3),pp.686–697.

Westling, G. and Johansson, R.S. 1984. Factors influencing the force control during precision grip. Experimental brain research. 53(2),pp.277–284.

Westling, G. and Johansson, R.S. 1987. Responses in glabrous skin mechanoreceptors during precision grip in humans. Experimental Brain Research. 66(1),pp.128–140.

Wiener, J.M., Hanley, R.J., Clark, R. and Van Nostrand, J.F. 1990. Measuring the activities of daily living: Comparisons across national surveys. Journals of Gerontology. 45(6),pp.229–237.

Wing, A.M. and Lederman, S. 2009. Points for Precision Grip. In D. A. Nowak & J. Hermsdörfer, Sensorimotor Control of Grasping 1st ed. Cambridge: Cambridge Press.

Winter, D.A. 2009. Biomechanics and motor control of human movement 4th ed. New Jersey: John Wiley & Sons, Inc.

Witney, A.G., Wing, A., Thonnard, J.-L. and Smith, A.M. 2004. The cutaneous contribution to adaptive precision grip. Trends in neurosciences. 27(10),pp.637–43.

Witney, A.G. and Wolpert, D.M. 2007. The effect of externally generated loading on predictive grip force modulation. Neuroscience Letters. 414(1),pp.10–15.

Wolpert, D.M. 2007. Probabilistic models in human sensorimotor control. Human movement science. 26(4),pp.511–24.

Wolpert, D.M., Miall, R.C. and Kawato, M. 1998. Internal models in the cerebellum. Trends in Cognitive Sciences. 2(9),pp.338–347.

Wu, Y., Chen, Y., Ye, Y., Yan, T. and Song, R. 2018. Age-Related Differences in Complexity during Handgrip Control Using Multiscale Entropy. IEEE Access. 6,pp.45552–45561.

Zatsiorsky, V.M., Gao, F. and Latash, M.L. 2003. Finger force vectors in multi-finger prehension. . 36,pp.1745–1749.

Zatsiorsky, V.M. and Latash, M.L. 2009. Ditgit Forces in Multi-Digit Grasps In: D. A. Nowak and J. Hermsdörfer, eds. Sensorimotor Control of Grasping. Cambridge: Cambridge University Press, pp. 33–51.

Zuur, A.F., Ieno, E.N. and Elphick, C.S. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution. 1(1),pp.3–14.

R package references

Bates, P. Sarkar D, R Core Team (2019). Nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-140, https://CRAN.R-project.org/package=nlme

Kassambara, A. and Mundt, F. (2017). factoextra: Extract and Visualize the Results of Multivariate Data Analyses. R package version 1.0.5. https://CRAN.R-project.org/package=factoextra

Morales, M. R Development Core Team and Murdoch. D. (2017). sciplot: Scientific Graphing Functions for Factorial Designs. R package version 1.1-1. https://CRAN.R-project.org/package=sciplot

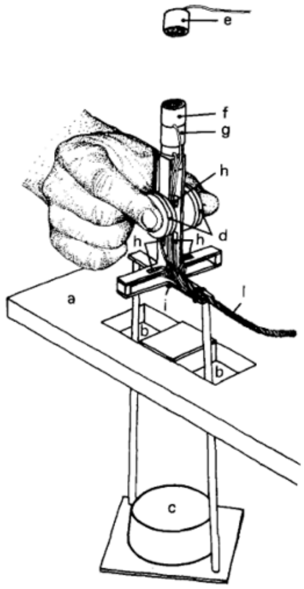
Revelle, W. (2018) psych: Procedures for Personality and Psychological Research, Northwestern University, Evanston, Illinois, USA, https://CRAN.R-project.org/package=psych

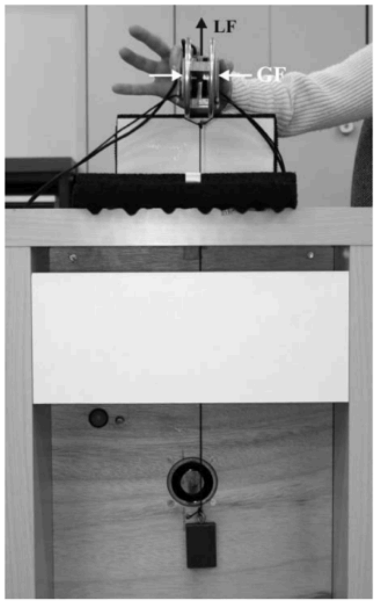
Signal developers (2013). signal: Signal processing. http://r-forge.r-project.org/projects/signal/

Chapter 9 – List of Appendices

9.1 Example manipulanda with external mass

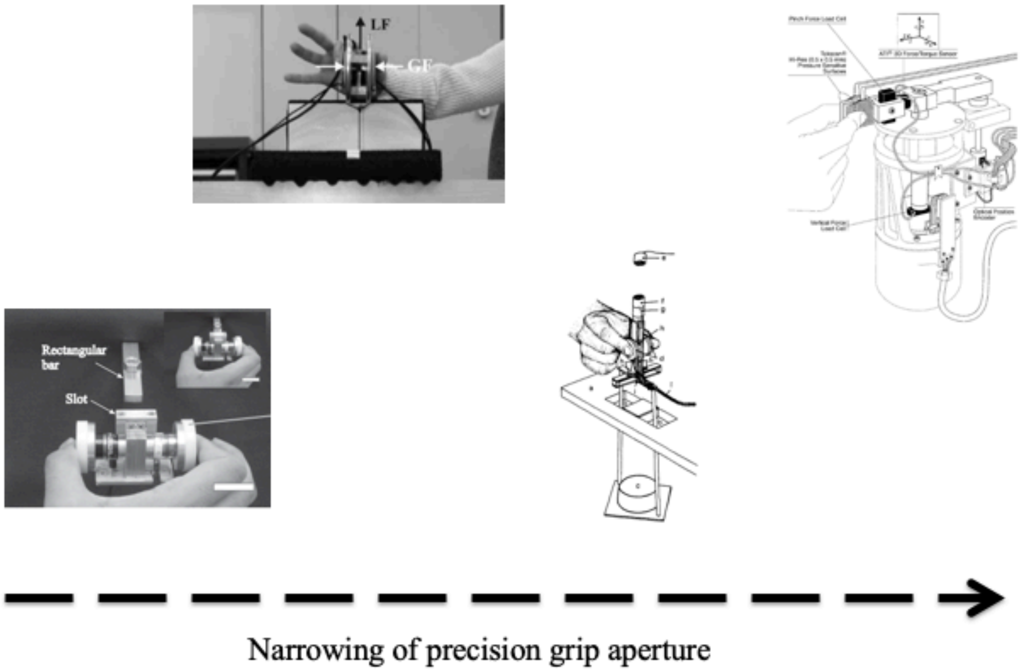
Pictured below are manipulanda with external masses placed on a loading tray, positioned under the table (left) (Johansson and Westling, 1984) and connected using a string (right) (Bleyenheuft and Thonnard, 2010). Both provide ways of adapting mass, whilst occluding the change in mass from the user, but both also limit the portability of the devices.





9.2 Example manipulanda with varying grip aperture

Pictured below are four manipulanda from previous research from left to right: (Parikh and Cole, 2012; Bleyenheuft and Thonnard, 2010; Johansson and Westling, 1984; Monzée et al., 2003). They show the wide range of grip apertures that have been used within previous research.



9.3 Chapter six full ANOVA results

Appendix 9.3 contains tables showing all main effects and interactions of the repeated measures analysis ran for experiment two (chapter 6).

Table 9.1: Repeated measures mixed ANOVA results for log transformation of loading time.

Effect	F	df	Sig. level	Partial Eta squared
Group	9.55	1, 38	0.004	.20
Condition	134.60	1, 38	< 0.001	.78
Condition * group	.97	1, 38	0.33	.03
Hand	0.07	1, 38	0.79	.00
Hand * group	0.30	1, 38	0.86	.00
Mass	76.7	1, 38	< 0.001	.67
Mass * group	0.31	1, 38	0.58	.01
Condition * hand	0.16	1, 38	0.67	.00
Condition * hand * group	0.18	1, 38	0.67	.01
Condition * mass	2.35	1, 38	0.13	.06
Condition * mass * group	1.54	1, 38	0.22	.04
Hand * mass	0.22	1, 38	0.64	.01
Hand * mass * group	0.57	1, 38	0.46	.02
Condition * hand * mass	0.12	1, 38	0.73	.00
Condition * hand * mass * group	0.61	1, 38	0.44	.02

Table 9.2: Repeated measures mixed ANOVA results for transport time.

Effect	F	df	Sig. level	Partial Eta squared
Group	0.12	1, 38	0.73	.00
Condition	5.61	1, 38	0.02	.13
Condition * group	1.22	1, 38	0.28	.03
Hand	1.39	1, 38	0.35	.04
Hand * group	0.75	1, 38	0.39	.02
Mass	0.06	1, 38	0.81	.00
Mass * group	0.45	1, 38	0.51	.01
Condition * hand	3.79	1, 38	0.06	.09
Condition * hand * group	4.78	1, 38	0.04	.11
Condition * mass	0.01	1, 38	0.94	.00
Condition * mass * group	0.11	1, 38	0.75	.00
Hand * mass	0.25	1, 38	0.62	.01
Hand * mass * group	0.08	1, 38	0.78	.02
Condition * hand * mass	0.04	1, 38	0.84	.00
Condition * hand * mass * group	1.41	1, 38	0.24	.04

Table 9.3: Repeated measures mixed ANOVA results for stable time.

Effect	F	df	Sig. level	Partial Eta squared
Group	0.56	1, 38	0.46	.02
Condition	3.94	1, 38	0.06	.01
Condition * group	2.20	1, 38	0.15	.06
Hand	0.14	1, 38	0.71	.00
Hand * group	0.72	1, 38	0.40	.02
Mass	0.02	1, 38	0.89	.00
Mass * group	0.01	1, 38	0.91	.01
Condition * hand	1.00	1, 38	0.32	.03
Condition * hand * group	5.20	1, 38	0.03	.12
Condition * mass	0.36	1, 38	0.55	.01
Condition * mass * group	0.03	1, 38	0.55	.01
Hand * mass	2.27	1, 38	0.14	.06
Hand * mass * group	0.61	1, 38	0.44	.02
Condition * hand * mass	1.56	1, 38	0.22	.04
Condition * hand * mass * group	1.80	1, 38	0.18	.05

Table 9.4: Repeated measures mixed ANOVA results for replace time.

Effect	F	df	Sig. level	Partial Eta squared
Group	0.00	1, 38	0.95	.00
Condition	48.01	1, 38	< 0.001	.56
Condition * group	0.99	1, 38	0.33	.03
Hand	1.24	1, 38	0.27	.03
Hand * group	0.20	1, 38	0.66	.01
Mass	1.15	1, 38	0.29	.03
Mass * group	0.07	1, 38	0.79	.00
Condition * hand	1.71	1, 38	0.20	.04
Condition * hand * group	0.30	1, 38	0.59	.01
Condition * mass	0.49	1, 38	0.49	.01
Condition * mass * group	0.01	1, 38	0.92	.00
Hand * mass	0.15	1, 38	0.70	.00
Hand * mass * group	0.17	1, 38	0.69	.00
Condition * hand * mass	1.36	1, 38	0.25	.04
Condition * hand * mass * group	0.01	1, 38	0.76	.00

Table 9.5: Repeated measures mixed ANOVA results for release time.

Effect	F	df	Sig. level	Partial Eta squared
Group	1.12	1, 38	0.30	.03
Condition	8.02	1, 38	0.007	.17
Condition * group	0.12	1, 38	0.74	.00
Hand	0.01	1, 38	0.75	.00
Hand * group	5.26	1, 38	0.027	.12
Mass	3.79	1, 38	0.06	.09
Mass * group	0.32	1, 38	0.58	.01
Condition * hand	0.01	1, 38	0.93	.00
Condition * hand * group	0.43	1, 38	0.52	.01
Condition * mass	2.94	1, 38	0.10	.07
Condition * mass * group	0.80	1, 38	0.38	.02
Hand * mass	0.11	1, 38	0.74	.00
Hand * mass * group	0.48	1, 38	0.49	.01
Condition * hand * mass	1.13	1, 38	0.29	.03
Condition * hand * mass * group	0.02	1, 38	0.90	.00

Table 9.6: Repeated measures mixed ANOVA results for log transformation of path length.

Effect	F	df	Sig. level	Partial Eta squared
Group	7.05	1, 38	0.01	.16
Condition	0.10	1, 38	0.75	.00
Condition * group	2.34	1, 38	0.13	.06
Hand	17.53	1, 38	< 0.001	.32
Hand * group	1.14	1, 38	0.29	.03
Mass	1.63	1, 38	0.21	.04
Mass * group	0.53	1, 38	0.21	.04
Condition * hand	0.00	1, 38	0.95	.00
Condition * hand * group	2.72	1, 38	0.11	.07
Condition * mass	0.26	1, 38	0.61	.00
Condition * mass * group	1.20	1, 38	0.28	.03
Hand * mass	1.68	1, 38	0.20	.04
Hand * mass * group	0.31	1, 38	0.58	.01
Condition * hand * mass	1.49	1, 38	0.23	.04
Condition * hand * mass * group	0.63	1, 38	0.43	.02

Table 9.7: Repeated measures mixed ANOVA results for hold height.

Effect	F	df	Sig. level	Partial Eta squared
Group	1.06	1, 38	0.31	.03
Condition	4.10	1, 38	0.05	.10
Condition * group	0.87	1, 38	0.36	.02
Hand	0.45	1, 38	0.51	.01
Hand * group	0.88	1, 38	0.36	.02
Mass	0.25	1, 38	0.62	.01
Mass * group	2.48	1, 38	0.12	.06
Condition * hand	0.31	1, 38	0.58	.01
Condition * hand * group	0.04	1, 38	0.85	.00
Condition * mass	0.01	1, 38	0.76	.00
Condition * mass * group	1.20	1, 38	0.28	.00
Hand * mass	0.13	1, 38	0.72	.00
Hand * mass * group	1.71	1, 38	0.20	.04
Condition * hand * mass	0.16	1, 38	0.69	.00
Condition * hand * mass * group	2.01	1, 38	0.43	.05

Table 9.8: Repeated measures mixed ANOVA results for log transformation of peak grip force.

Effect	F	df	Sig. level	Partial Eta squared
Group	15.81	1, 38	< 0.001	.29
Condition	7.00	1, 38	0.01	.16
Condition * group	1.29	1, 38	0.26	.03
Hand	0.06	1, 38	0.82	.00
Hand * group	1.65	1, 38	0.21	.04
Mass	206.20	1, 38	< 0.001	.84
Mass * group	0.45	1, 38	0.51	.01
Condition * hand	2.09	1, 38	0.16	.05
Condition * hand * group	0.10	1, 38	0.75	.00
Condition * mass	0.64	1, 38	0.43	.02
Condition * mass * group	0.00	1, 38	0.99	.00
Hand * mass	0.59	1, 38	0.45	.02
Hand * mass * group	2.79	1, 38	0.10	.07
Condition * hand * mass	1.94	1, 38	0.17	.05
Condition * hand * mass * group	0.49	1, 38	0.49	.01

Table 9.9: Repeated measures mixed ANOVA results for log transformation of time to peak grip force.

Effect	F	df	Sig. level	Partial Eta squared
Group	1.72	1, 38	0.20	.04
Condition	6.22	1, 38	0.017	.14
Condition * group	0.03	1, 38	0.88	.00
Hand	2.71	1, 38	0.11	.07
Hand * group	0.00	1, 38	0.97	.00
Mass	1.27	1, 38	0.27	.03
Mass * group	0.17	1, 38	0.69	.00
Condition * hand	0.04	1, 38	0.85	.00
Condition * hand * group	1.14	1, 38	0.29	.03
Condition * mass	0.06	1, 38	0.81	.00
Condition * mass * group	0.00	1, 38	0.97	.00
Hand * mass	3.07	1, 38	0.09	.08
Hand * mass * group	0.05	1, 38	0.82	.00
Condition * hand * mass	0.51	1, 38	0.48	.01
Condition * hand * mass * group	0.09	1, 38	0.77	.00

Table 9.10: Repeated measures mixed ANOVA results for peak load force.

Effect	F	df	Sig. level	Partial Eta squared
Group	0.70	1, 38	0.41	.02
Condition	4.79	1, 38	0.04	.11
Condition * group	0.80	1, 38	0.39	.02
Hand	0.38	1, 38	0.54	.01
Hand * group	0.22	1, 38	0.64	.01
Mass	9737.00	1, 38	< 0.001	1.00
Mass * group	0.61	1, 38	0.44	.02
Condition * hand	2.16	1, 38	0.15	.05
Condition * hand * group	1.51	1, 38	0.23	.04
Condition * mass	0.27	1, 38	0.81	.01
Condition * mass * group	0.15	1, 38	0.97	.00
Hand * mass	0.07	1, 38	0.09	.00
Hand * mass * group	0.04	1, 38	0.82	.00
Condition * hand * mass	0.84	1, 38	0.37	.02
Condition * hand * mass * group	0.00	1, 38	0.96	.00

Table 9.11: Repeated measures mixed ANOVA results for log transformation of time to peak load force.

Effect	F	df	Sig. level	Partial Eta squared
Group	12.48	1, 38	0.001	.25
Condition	136.33	1, 38	0.10	.78
Condition * group	2.78	1, 38	0.10	.07
Hand	0.46	1, 38	0.50	.01
Hand * group	0.06	1, 38	0.81	.00
Mass	78.65	1, 38	< 0.001	.67
Mass * group	0.11	1, 38	0.75	.00
Condition * hand	0.08	1, 38	0.78	.00
Condition * hand * group	0.03	1, 38	0.86	.00
Condition * mass	1.38	1, 38	0.25	.04
Condition * mass * group	1.85	1, 38	0.18	.05
Hand * mass	0.11	1, 38	0.75	.00
Hand * mass * group	0.36	1, 38	0.55	.01
Condition * hand * mass	0.14	1, 38	0.71	.00
Condition * hand * mass * group	0.38	1, 38	0.54	.01

Table 9.12: Repeated measures mixed ANOVA results for log transformation of grip force to load force ratio (GF:LF) at start of lift.

Effect	F	df	Sig. level	Partial Eta squared
Group	16.55	1, 38	< 0.001	.30
Condition	4.46	1, 38	0.04	.11
Condition * group	0.86	1, 38	0.36	.02
Hand	0.28	1, 38	0.60	.01
Hand * group	0.20	1, 38	0.66	.00
Mass	32.44	1, 38	< 0.001	.46
Mass * group	0.35	1, 38	0.56	.01
Condition * hand	2.48	1, 38	0.12	.06
Condition * hand * group	0.47	1, 38	0.50	.01
Condition * mass	1.60	1, 38	0.21	.04
Condition * mass * group	0.19	1, 38	0.66	.01
Hand * mass	0.50	1, 38	0.48	.01
Hand * mass * group	1.05	1, 38	0.31	.03
Condition * hand * mass	1.55	1, 38	0.22	.04
Condition * hand * mass * group	0.67	1, 38	0.42	.02

Table 9.13: Repeated measures mixed ANOVA results for log transformation of grip force to load force ratio (GF:LF) during stable phase.

Effect	F	df	Sig. level	Partial Eta squared
Group	16.31	1, 38	< 0.001	.30
Condition	1.15	1, 38	0.29	.03
Condition * group	2.79	1, 38	0.10	.07
Hand	4.72	1, 38	0.036	.11
Hand * group	0.08	1, 38	0.78	.00
Mass	37.08	1, 38	< 0.001	.49
Mass * group	0.82	1, 38	0.37	.02
Condition * hand	0.05	1, 38	0.83	.00
Condition * hand * group	0.11	1, 38	0.74	.00
Condition * mass	0.34	1, 38	0.57	.01
Condition * mass * group	0.01	1, 38	0.91	.00
Hand * mass	4.75	1, 38	0.036	.11
Hand * mass * group	0.13	1, 38	0.73	.00
Condition * hand * mass	0.53	1, 38	0.47	.01
Condition * hand * mass * group	1.24	1, 38	0.27	.03

Table 9.14: Repeated measures mixed ANOVA results for log transformation of safety margin during stable phase.

Effect	F	df	Sig. level	Partial Eta squared
Group	4.82	1, 38	0.034	.11
Condition	0.37	1, 38	0.55	.01
Condition * group	0.93	1, 38	0.34	.02
Hand	6.43	1, 38	0.015	.15
Hand * group	0.01	1, 38	0.94	.00
Mass	25.05	1, 38	< 0.001	.40
Mass * group	0.07	1, 38	0.80	.00
Condition * hand	0.22	1, 38	0.64	.01
Condition * hand * group	0.51	1, 38	0.48	.01
Condition * mass	0.00	1, 38	0.95	.00
Condition * mass * group	0.14	1, 38	0.71	.00
Hand * mass	1.99	1, 38	0.17	.05
Hand * mass * group	0.75	1, 38	0.39	.02
Condition * hand * mass	0.56	1, 38	0.46	.01
Condition * hand * mass * group	0.22	1, 38	0.64	.00

Table 9.15: Repeated measures mixed ANOVA results for peak cross-correlation coefficient.

Effect	F	df	Sig. level	Partial Eta squared
Group	5.46	1, 38	0.025	.13
Condition	2.77	1, 38	0.10	.07
Condition * group	0.60	1, 38	0.45	.02
Hand	2.68	1, 38	0.11	.07
Hand * group	0.15	1, 38	0.70	.00
Mass	23.83	1, 38	< 0.001	.39
Mass * group	1.00	1, 38	0.32	.03
Condition * hand	0.20	1, 38	0.66	.01
Condition * hand * group	0.23	1, 38	0.64	.01
Condition * mass	0.67	1, 38	0.42	.02
Condition * mass * group	0.02	1, 38	0.90	.00
Hand * mass	0.34	1, 38	0.56	.01
Hand * mass * group	0.20	1, 38	0.66	.01
Condition * hand * mass	0.12	1, 38	0.74	.00
Condition * hand * mass * group	1.02	1, 38	0.32	.03

Table 9.16: Repeated measures mixed ANOVA results for time-shift of peak cross-correlation value.

Effect	F	df	Sig. level	Partial Eta squared
Group	4.34	1, 38	0.04	.10
Condition	0.12	1, 38	0.74	.00
Condition * group	0.17	1, 38	0.68	.01
Hand	0.00	1, 38	1.00	.00
Hand * group	3.47	1, 38	0.07	.00
Mass	0.30	1, 38	0.59	.01
Mass * group	0.69	1, 38	0.41	.02
Condition * hand	6.14	1, 38	0.018	.14
Condition * hand * group	0.77	1, 38	0.39	.02
Condition * mass	0.17	1, 38	0.68	.00
Condition * mass * group	1.27	1, 38	0.27	.03
Hand * mass	2.22	1, 38	0.14	.06
Hand * mass * group	1.34	1, 38	0.25	.03
Condition * hand * mass	2.07	1, 38	0.16	.05
Condition * hand * mass * group	0.26	1, 38	0.62	.01

Table 9.17: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 2 during the dynamic phase.

Effect	F	df	Sig. level
Group	0.69	1, 30	0.41
Condition	1.58	1, 173	0.21
Hand	0.01	1, 173	0.93
Mass	1.02	1, 173	0.31
Group * condition	0.40	1, 173	0.53
Group * hand	0.08	1, 173	0.78
Condition * hand	0.70	1, 173	0.40
Group * mass	0.68	1, 173	0.41
Condition * mass	0.82	1, 173	0.37
Hand * mass	0.81	1, 173	0.37
Group * condition * hand	0.01	1, 173	0.94
Group * condition * mass	0.64	1, 173	0.42
Group * hand * mass	0.08	1, 173	0.78
Condition * hand * mass	0.56	1, 173	0.46
Group * condition * hand * mass	0.64	1, 173	0.42

Table 9.18: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 2 and 3 during the dynamic phase.

Effect	F	df	Sig. level
Group	4.78	1, 30	0.037
Condition	0.01	1, 173	0.91
Hand	0.00	1, 173	0.99
Mass	0.17	1, 173	0.68
Group * condition	0.07	1, 173	0.80
Group * hand	2.43	1, 173	0.12
Condition * hand	0.42	1, 173	0.51
Group * mass	1.41	1, 173	0.24
Condition * mass	0.32	1, 173	0.57
Hand * mass	0.06	1, 173	0.81
Group * condition * hand	0.45	1, 173	0.50
Group * condition * mass	0.60	1, 173	0.44
Group * hand * mass	0.65	1, 173	0.42
Condition * hand * mass	1.31	1, 173	0.25
Group * condition * hand * mass	0.02	1, 173	0.86

Table 9.19: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 3 during the dynamic phase.

Effect	F	df	Sig. level
Group	0.05	1, 30	0.82
Condition	1.77	1, 173	0.18
Hand	2.28	1, 173	0.13
Mass	0.17	1, 173	0.67
Group * condition	3.67	1, 173	0.057
Group * hand	0.26	1, 173	0.61
Condition * hand	1.54	1, 173	0.22
Group * mass	4.93	1, 173	0.028
Condition * mass	0.09	1, 173	0.76
Hand * mass	0.13	1, 173	0.72
Group * condition * hand	0.49	1, 173	0.48
Group * condition * mass	1.46	1, 173	0.22
Group * hand * mass	0.02	1, 173	0.89
Condition * hand * mass	0.21	1, 173	0.64
Group * condition * hand * mass	0.03	1, 173	0.85

Table 9.20: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 2 during the stable phase.

Effect	F	df	Sig. level
Group	0.00	1, 30	0.97
Condition	0.39	1, 173	0.53
Hand	0.06	1, 173	0.81
Mass	0.64	1, 173	0.42
Group * condition	0.21	1, 173	0.65
Group * hand	0.76	1, 173	0.38
Condition * hand	2.04	1, 173	0.16
Group * mass	0.00	1, 173	0.98
Condition * mass	0.43	1, 173	0.51
Hand * mass	0.44	1, 173	0.51
Group * condition * hand	0.02	1, 173	0.88
Group * condition * mass	0.02	1, 173	0.89
Group * hand * mass	1.21	1, 173	0.27
Condition * hand * mass	0.01	1, 173	0.92
Group * condition * hand * mass	0.00	1, 173	0.97

Table 9.21: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 2 and 3 during the stable phase.

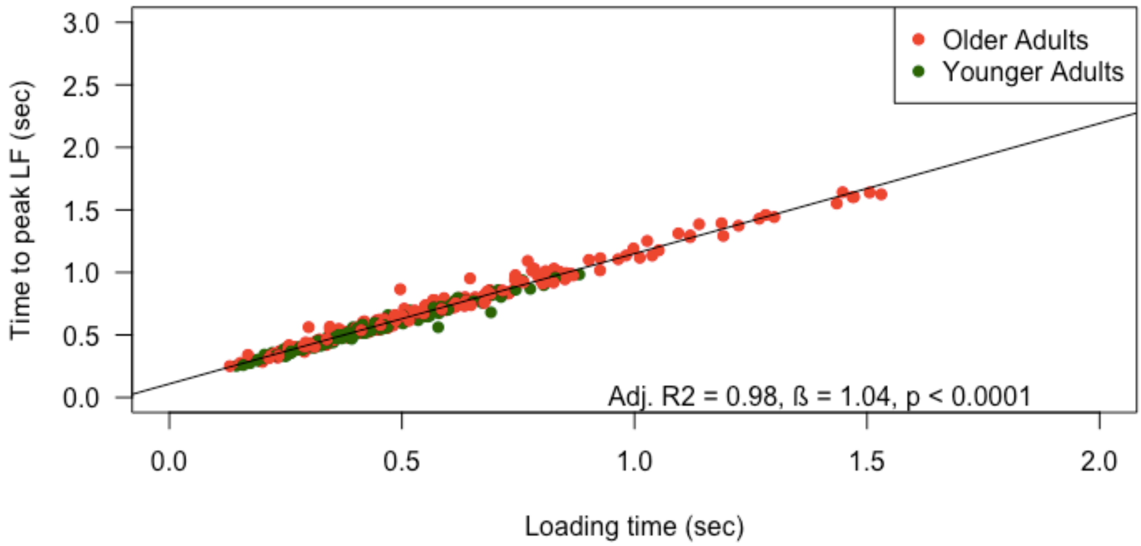
Effect	F	df	Sig. level
Group	0.31	1, 30	0.58
Condition	0.96	1, 173	0.33
Hand	1.93	1, 173	0.17
Mass	1.21	1, 173	0.27
Group * condition	0.40	1, 173	0.53
Group * hand	1.37	1, 173	0.24
Condition * hand	0.00	1, 173	0.98
Group * mass	0.01	1, 173	0.91
Condition * mass	0.32	1, 173	0.57
Hand * mass	0.92	1, 173	0.33
Group * condition * hand	0.01	1, 173	0.92
Group * condition * mass	1.42	1, 173	0.23
Group * hand * mass	0.03	1, 173	0.86
Condition * hand * mass	0.04	1, 173	0.85
Group * condition * hand * mass	0.44	1, 173	0.51

Table 9.22: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 3 during the stable phase.

Effect	F	df	Sig. level
Group	1.04	1, 30	0.32
Condition	4.58	1, 173	0.034
Hand	9.83	1, 173	0.002
Mass	1.47	1, 173	0.23
Group * condition	0.28	1, 173	0.60
Group * hand	10.58	1, 173	0.001
Condition * hand	0.45	1, 173	0.50
Group * mass	6.74	1, 173	0.01
Condition * mass	0.14	1, 173	0.71
Hand * mass	0.51	1, 173	0.48
Group * condition * hand	0.01	1, 173	0.90
Group * condition * mass	3.21	1, 173	0.08
Group * hand * mass	0.30	1, 173	0.59
Condition * hand * mass	2.28	1, 173	0.13
Group * condition * hand * mass	0.11	1, 173	0.74

9.4 Relationship between loading time and time to peak load force

A simple regression was performed between loading time and time to peak load force for all trials. The results show 98% of changes in time to peak load force being explained by the participant's loading time. Consequently, time to peak load force was removed from experiment three.



9.5 Chapter seven full ANOVA results

Appendix 9.5 contains tables showing all main effects and interactions of the repeated measures analysis ran for experiment three (chapter 7).

Table 9.23: Repeated measures mixed ANOVA results for loading time.

Effect	F	df	Sig. level
Group	7.94	2, 52	0.001
Condition	154.56	1, 364	< 0.001
Hand	0.11	1, 364	0.74
Mass	91.55	1, 364	< 0.001
Group * condition	0.77	2, 364	0.46
Group * hand	0.04	2, 364	0.96
Condition * hand	0.23	1, 364	0.64
Group * mass	0.28	2, 364	0.76
Condition * mass	1.24	1, 364	0.27
Hand * mass	0.20	1, 364	0.66
Group * condition * hand	0.19	2, 364	0.83
Group * condition * mass	0.19	2, 364	0.83
Group * hand * mass	1.55	2, 364	0.21
Condition * hand * mass	0.02	1, 364	0.89
Group * condition * hand * mass	2.82	2, 364	0.06

Table 9.24: Repeated measures mixed ANOVA results for transport time.

Effect	F	df	Sig. level
Group	0.02	2, 52	0.98
Condition	3.53	1, 364	0.06
Hand	0.90	1, 364	0.34
Mass	0.14	1, 364	0.71
Group * condition	2.29	2, 364	0.10
Group * hand	1.38	2, 364	0.25
Condition * hand	2.08	1, 364	0.15
Group * mass	1.11	2, 364	0.33
Condition * mass	0.00	1, 364	0.97
Hand * mass	0.67	1, 364	0.41
Group * condition * hand	0.43	2, 364	0.65
Group * condition * mass	0.16	2, 364	0.86
Group * hand * mass	0.39	2, 364	0.67
Condition * hand * mass	0.00	1, 364	0.96
Group * condition * hand * mass	4.03	2, 364	0.019

Table 9.25: Repeated measures mixed ANOVA results for stable time.

Effect	F	df	Sig. level
Group	1.70	2, 52	0.19
Condition	11.59	1, 364	< 0.001
Hand	0.43	1, 364	0.51
Mass	0.28	1, 364	0.60
Group * condition	2.31	2, 364	0.10
Group * hand	1.23	2, 364	0.29
Condition * hand	0.89	1, 364	0.35
Group * mass	1.42	2, 364	0.24
Condition * mass	0.50	1, 364	0.48
Hand * mass	1.57	1, 364	0.21
Group * condition * hand	1.83	2, 364	0.16
Group * condition * mass	0.00	2, 364	1.00
Group * hand * mass	0.33	2, 364	0.72
Condition * hand * mass	1.04	1, 364	0.31
Group * condition * hand * mass	1.78	2, 364	0.17

Table 9.26: Repeated measures mixed ANOVA results for replace time.

Effect	F	df	Sig. level
Group	1.33	2, 52	0.27
Condition	66.89	1, 364	< 0.001
Hand	0.52	1, 364	0.47
Mass	3.52	1, 364	0.61
Group * condition	0.60	2, 364	0.55
Group * hand	0.31	2, 364	0.73
Condition * hand	0.44	1, 364	0.51
Group * mass	1.15	2, 364	0.32
Condition * mass	1.60	1, 364	0.20
Hand * mass	1.71	1, 364	0.19
Group * condition * hand	0.16	2, 364	0.86
Group * condition * mass	2.64	2, 364	0.07
Group * hand * mass	0.67	2, 364	0.51
Condition * hand * mass	1.54	1, 364	0.22
Group * condition * hand * mass	1.28	2, 364	0.28

Table 9.27: Repeated measures mixed ANOVA results for the log transformation of release time.

Effect	F	df	Sig. level
Group	1.00	2, 52	0.38
Condition	23.13	1, 364	< 0.001
Hand	1.61	1, 364	0.21
Mass	1.64	1, 364	0.20
Group * condition	2.15	2, 364	0.21
Group * hand	1.45	2, 364	0.24
Condition * hand	0.18	1, 364	0.67
Group * mass	2.09	2, 364	0.12
Condition * mass	2.49	1, 364	0.12
Hand * mass	0.49	1, 364	0.48
Group * condition * hand	0.08	2, 364	0.93
Group * condition * mass	0.11	2, 364	0.90
Group * hand * mass	2.15	2, 364	0.12
Condition * hand * mass	1.07	1, 364	0.30
Group * condition * hand * mass	1.39	2, 364	0.25

Table 9.28: Repeated measures mixed ANOVA results for hold height.

Effect	F	df	Sig. level
Group	0.15	2, 52	0.86
Condition	7.00	1, 364	0.009
Hand	0.04	1, 364	0.85
Mass	0.06	1, 364	0.80
Group * condition	2.19	2, 364	0.11
Group * hand	0.10	2, 364	0.90
Condition * hand	0.51	1, 364	0.48
Group * mass	3.70	2, 364	0.026
Condition * mass	1.23	1, 364	0.27
Hand * mass	0.00	1, 364	0.99
Group * condition * hand	1.66	2, 364	0.19
Group * condition * mass	2.83	2, 364	0.06
Group * hand * mass	0.41	2, 364	0.67
Condition * hand * mass	0.00	1, 364	0.97
Group * condition * hand * mass	0.72	2, 364	0.49

Table 9.29: Repeated measures mixed ANOVA results for log transformation of path length.

Effect	F	df	Sig. level
Group	2.21	2, 52	0.12
Condition	0.15	1, 364	0.70
Hand	13.97	1, 364	< 0.001
Mass	4.92	1, 364	0.027
Group * condition	0.91	2, 364	0.40
Group * hand	2.92	2, 364	0.06
Condition * hand	0.02	1, 364	0.88
Group * mass	1.61	2, 364	0.20
Condition * mass	0.07	1, 364	0.79
Hand * mass	0.89	1, 364	0.35
Group * condition * hand	3.02	2, 364	0.05
Group * condition * mass	0.64	2, 364	0.53
Group * hand * mass	1.12	2, 364	0.33
Condition * hand * mass	1.50	1, 364	0.22
Group * condition * hand * mass	0.32	2, 364	0.73

Table 9.30: Repeated measures mixed ANOVA results for log transformation of peak grip force.

Effect	F	df	Sig. level
Group	11.16	2, 52	< 0.001
Condition	0.18	1, 364	0.67
Hand	0.55	1, 364	0.66
Mass	264.26	1, 364	< 0.001
Group * condition	5.94	2, 364	0.003
Group * hand	1.54	2, 364	0.22
Condition * hand	1.04	1, 364	0.31
Group * mass	0.55	2, 364	0.58
Condition * mass	0.05	1, 364	0.82
Hand * mass	0.00	1, 364	0.98
Group * condition * hand	0.47	2, 364	0.63
Group * condition * mass	0.89	2, 364	0.41
Group * hand * mass	2.64	2, 364	0.07
Condition * hand * mass	0.46	1, 364	0.50
Group * condition * hand * mass	0.08	2, 364	0.98

Table 9.31: Repeated measures mixed ANOVA results for log transformation of time to peak grip force.

Effect	F	df	Sig. level
Group	2.23	2, 52	0.12
Condition	9.41	1, 364	0.002
Hand	1.63	1, 364	0.20
Mass	1.27	1, 364	0.26
Group * condition	0.05	2, 364	0.95
Group * hand	0.17	2, 364	0.84
Condition * hand	0.34	1, 364	0.56
Group * mass	0.65	2, 364	0.52
Condition * mass	0.03	1, 364	0.87
Hand * mass	2.56	1, 364	0.11
Group * condition * hand	0.26	2, 364	0.77
Group * condition * mass	0.08	2, 364	0.92
Group * hand * mass	0.26	2, 364	0.77
Condition * hand * mass	0.10	1, 364	0.75
Group * condition * hand * mass	0.47	2, 364	0.63

Table 9.32: Repeated measures mixed ANOVA results for log transformation of peak load force.

Effect	F	df	Sig. level
Group	0.32	2, 52	0.73
Condition	3.38	1, 364	0.07
Hand	0.21	1, 364	0.65
Mass	7700.77	1, 364	< 0.001
Group * condition	0.28	2, 364	0.76
Group * hand	0.07	2, 364	0.93
Condition * hand	0.02	1, 364	0.89
Group * mass	0.27	2, 364	0.77
Condition * mass	2.84	1, 364	0.09
Hand * mass	0.01	1, 364	0.93
Group * condition * hand	1.11	2, 364	0.33
Group * condition * mass	1.44	2, 364	0.24
Group * hand * mass	0.18	2, 364	0.83
Condition * hand * mass	0.18	1, 364	0.67
Group * condition * hand * mass	0.22	2, 364	0.81

Table 9.33: Repeated measures mixed ANOVA results for log transformation of grip force to load force ratio during the start of the lift.

Effect	F	df	Sig. level
Group	11.90	2, 52	< 0.001
Condition	0.27	1, 364	0.61
Hand	0.85	1, 364	0.36
Mass	46.49	1, 364	< 0.001
Group * condition	4.81	2, 364	0.009
Group * hand	1.09	2, 364	0.34
Condition * hand	1.08	1, 364	0.30
Group * mass	0.27	2, 364	0.77
Condition * mass	0.02	1, 364	0.88
Hand * mass	0.06	1, 364	0.80
Group * condition * hand	0.90	2, 364	0.41
Group * condition * mass	1.66	2, 364	0.19
Group * hand * mass	2.23	2, 364	0.11
Condition * hand * mass	0.33	1, 364	0.57
Group * condition * hand * mass	0.39	2, 364	0.68

Table 9.34: Repeated measures mixed ANOVA results for log transformation of grip force to load force ratio during the stable phase of the lift.

Effect	F	df	Sig. level
Group	11.71	2, 52	< 0.001
Condition	0.89	1, 364	0.35
Hand	1.00	1, 364	0.32
Mass	58.05	1, 364	< 0.001
Group * condition	4.61	2, 364	0.01
Group * hand	0.23	2, 364	0.79
Condition * hand	0.65	1, 364	0.42
Group * mass	0.79	2, 364	0.45
Condition * mass	0.37	1, 364	0.55
Hand * mass	1.88	1, 364	0.17
Group * condition * hand	0.69	2, 364	0.50
Group * condition * mass	2.10	2, 364	0.12
Group * hand * mass	2,18	2, 364	0.11
Condition * hand * mass	0.00	1, 364	0.99
Group * condition * hand * mass	0.24	2, 364	0.79

Table 9.35: Repeated measures mixed ANOVA results for log transformation of safety margin.

Effect	F	df	Sig. level
Group	4.71	2, 52	0.013
Condition	2.88	1, 364	0.09
Hand	1.29	1, 364	0.26
Mass	17.52	1, 364	< 0.001
Group * condition	4.22	2, 364	0.016
Group * hand	0.38	2, 364	0.68
Condition * hand	0.54	1, 364	0.46
Group * mass	0.04	2, 364	0.96
Condition * mass	0.02	1, 364	0.89
Hand * mass	0.57	1, 364	0.45
Group * condition * hand	0.74	2, 364	0.47
Group * condition * mass	0.98	2, 364	0.38
Group * hand * mass	1.93	2, 364	0.15
Condition * hand * mass	0.02	1, 364	0.90
Group * condition * hand * mass	0.24	2, 364	0.79

Table 9.36: Repeated measures mixed ANOVA results for peak cross-correlation coefficient.

Effect	F	df	Sig. level
Group	6.99	2, 52	0.002
Condition	1.03	1, 364	0.31
Hand	1.41	1, 364	0.24
Mass	32.49	1, 364	< 0.001
Group * condition	1.23	2, 364	0.29
Group * hand	0.19	2, 364	0.83
Condition * hand	0.41	1, 364	0.52
Group * mass	0.69	2, 364	0.50
Condition * mass	1.25	1, 364	0.26
Hand * mass	0.90	1, 364	0.34
Group * condition * hand	0.16	2, 364	0.86
Group * condition * mass	0.21	2, 364	0.81
Group * hand * mass	0.54	2, 364	0.59
Condition * hand * mass	0.00	1, 364	0.95
Group * condition * hand * mass	2.19	2, 364	0.11

Table 9.37: Repeated measures mixed ANOVA results for time-shift of peak cross-correlation coefficient.

Effect	F	df	Sig. level
Group	0.30	2, 52	0.74
Condition	0.34	1, 364	0.56
Hand	0.15	1, 364	0.70
Mass	0.26	1, 364	0.61
Group * condition	1.13	2, 364	0.32
Group * hand	3.70	2, 364	0.026
Condition * hand	0.54	1, 364	0.46
Group * mass	0.42	2, 364	0.65
Condition * mass	0.30	1, 364	0.59
Hand * mass	1.66	1, 364	0.20
Group * condition * hand	1.30	2, 364	0.27
Group * condition * mass	1.47	2, 364	0.23
Group * hand * mass	0.39	2, 364	0.68
Condition * hand * mass	0.54	1, 364	0.46
Group * condition * hand * mass	0.87	2, 364	0.42

Table 9.38: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 2 during the dynamic phase.

Effect	F	df	Sig. level
Group	2.01	2, 41	0.15
Condition	1.54	1, 240	0.22
Hand	0.54	1, 240	0.46
Mass	10.36	1, 240	0.002
Group * condition	1.62	2, 240	0.20
Group * hand	0.15	2, 240	0.86
Condition * hand	1.03	1, 240	0.31
Group * mass	1.47	2, 240	0.86
Condition * mass	0.11	1, 240	0.75
Hand * mass	2.22	1, 240	0.14
Group * condition * hand	1.09	2, 240	0.34
Group * condition * mass	0.01	2, 240	0.99
Group * hand * mass	0.19	2, 240	0.83
Condition * hand * mass	1.33	1, 240	0.25
Group * condition * hand * mass	0.47	2, 240	0.62

Table 9.39: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 2 and 3 during the dynamic phase.

Effect	F	df	Sig. level
Group	5.65	2, 41	0.007
Condition	0.67	1, 240	0.41
Hand	1.50	1, 240	0.22
Mass	0.02	1, 240	0.89
Group * condition	0.23	2, 240	0.79
Group * hand	1.39	2, 240	0.25
Condition * hand	1.86	1, 240	0.17
Group * mass	0.31	2, 240	0.73
Condition * mass	2.17	1, 240	0.14
Hand * mass	0.63	1, 240	0.43
Group * condition * hand	0.39	2, 240	0.68
Group * condition * mass	0.49	2, 240	0.61
Group * hand * mass	1.64	2, 240	0.20
Condition * hand * mass	2.29	1, 240	0.13
Group * condition * hand * mass	0.55	2, 240	0.58

Table 9.40: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 3 during the dynamic phase.

Effect	F	df	Sig. level
Group	0.22	2, 41	0.80
Condition	1.62	1, 240	0.20
Hand	2.08	1, 240	0.15
Mass	2.25	1, 240	0.13
Group * condition	3.41	2, 240	0.03
Group * hand	1.48	2, 240	0.22
Condition * hand	1.51	1, 240	0.22
Group * mass	2.76	2, 240	0.07
Condition * mass	0.00	1, 240	0.98
Hand * mass	0.07	1, 240	0.80
Group * condition * hand	0.65	2, 240	0.52
Group * condition * mass	1.26	2, 240	0.28
Group * hand * mass	1.36	2, 240	0.26
Condition * hand * mass	1.54	1, 240	0.21
Group * condition * hand * mass	1.07	2, 240	0.34

Table 9.41: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 2 during the stable phase.

Effect	F	df	Sig. level
Group	0.51	2, 41	0.60
Condition	1.43	1, 240	0.23
Hand	1.97	1, 240	0.16
Mass	0.03	1, 240	0.86
Group * condition	4.69	2, 240	0.01
Group * hand	0.36	2, 240	0.70
Condition * hand	3.61	1, 240	0.06
Group * mass	0.06	2, 240	0.95
Condition * mass	0.00	1, 240	0.96
Hand * mass	0.91	1, 240	0.34
Group * condition * hand	0.06	2, 240	0.94
Group * condition * mass	0.22	2, 240	0.80
Group * hand * mass	0.26	2, 240	0.77
Condition * hand * mass	0.01	1, 240	0.90
Group * condition * hand * mass	0.51	2, 240	0.60

Table 9.42: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 2 and 3 during the stable phase.

Effect	F	df	Sig. level
Group	0.14	2, 41	0.87
Condition	0.50	1, 240	0.48
Hand	1.79	1, 240	0.18
Mass	0.00	1, 240	1.00
Group * condition	0.51	2, 240	0.60
Group * hand	0.07	2, 240	0.93
Condition * hand	0.01	1, 240	0.92
Group * mass	0.13	2, 240	0.88
Condition * mass	1.70	1, 240	0.19
Hand * mass	6.50	1, 240	0.011
Group * condition * hand	4.07	2, 240	0.018
Group * condition * mass	1.08	2, 240	0.34
Group * hand * mass	0.53	2, 240	0.59
Condition * hand * mass	1.00	1, 240	0.32
Group * condition * hand * mass	0.06	2, 240	0.94

Table 9.43: Repeated measures mixed ANOVA results for correlation coefficient between muscle synergy 1 and 3 during the stable phase.

Effect	F	df	Sig. level
Group	0.04	2, 41	0.96
Condition	3.38	1, 240	0.07
Hand	0.03	1, 240	0.85
Mass	0.24	1, 240	0.62
Group * condition	1.37	2, 240	0.26
Group * hand	1.20	2, 240	0.30
Condition * hand	0.53	1, 240	0.47
Group * mass	1.71	2, 240	0.18
Condition * mass	0.11	1, 240	0.74
Hand * mass	0.38	1, 240	0.54
Group * condition * hand	0.56	2, 240	0.57
Group * condition * mass	1.90	2, 240	0.15
Group * hand * mass	0.57	2, 240	0.57
Condition * hand * mass	0.08	1, 240	0.78
Group * condition * hand * mass	1.24	2, 240	0.29