Development of a dexterity assessment method

by

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Abstract

This research was aimed at contributing to the understanding of dexterity through a scientific analysis of some of its more important features, as well as the development of viable methods to quantify these characteristics. The methods and procedures developed during this research were applied to evaluate traditional dexterity assessment methods, comparing dexterity features among tests and hand daily living tasks in order to characterise their reliability and robustness. The study makes use of visual, mathematical, and experimental methods to obtain, process, and analyse a series of hand function parameters that account for some of the main features that affect dexterity in modern daily living.

Furthermore, the designed methods and analysis techniques provide fundamental insights into our understanding of the relationships between motor coordination, movement, and hand function. More importantly, the data and conclusions derived from this research have the potential to aid in the development of improved health care practice, assistive technologies, and quality of life research, by providing practitioners and researchers with updated knowledge on human movement analysis, hand function, and dexterity.

The overall conclusion of this research is that the broad range of movements and patterns of the human hand, along with the infinite number of possible coordination strategies result in the need for the identification of movement patterns in order to accurately assess dexterity and hand function. Furthermore, although timed tests are time-efficient and cost-effective methods to measure dexterity, a truly objective and robust measurement of dexterity most cover all the factors and parameters that play a role in this phenomenon.

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Chapter 1

Background of the study

1.1 Introduction

Dexterity has been widely defined as both the ability to manipulate objects with the hands, and as harmonious in movements [1], however, as it will be established in this work, it is a very complex psychophysical phenomenon made of a series of features that have been grouped together and named through the years.

In his book *On dexterity and its development (1943),* Nicholai Bernstein developed a strict and precise definition and analysis of dexterity, taking into consideration motor control, biomechanics, and perception, and aiming at providing a highly practical overview for professionals in areas such as physical education and sport medicine. His work was recovered and revisited by Mark Latash and Michael Turvey [2], who added a historical and contemporary perspective on Bernstein's ideas, resulting in one of the most complete and valuable resources for researchers interested in contributing to the development of the study of dexterity.

Through his detailed analysis of dexterity and its features, some of which will be fully explained and studied in this work, Bernstein built an expanded and inclusive definition of dexterity:

"Dexterity is the ability to find a motor solution for an external situation, that is, to adequately solve an emerging motor problem accurately, quickly, rationally, and resourcefully".

Furthermore, Bernstein shows that dexterity is not a skill or a combination of skills. Dexterity is a capacity or an ability defining the relationship between the nervous system and skills. The level of motor dexterity defines how quickly and successfully a person can develop a certain motor skill and what level of perfection he or she is able to reach. Although dexterity is certainly an exercisable capacity, it is above all the skills, ruling them and defining their essential features.

To use just one word for this complex group of features is practical, because its components frequently belong together and have important internal relationships. However, such unification under one name brings with it a series of simplifications and assumptions that limit our real understanding of dexterity and with it, our ability to measure it accurately. While dexterity cannot be fully “discovered” as it was possible to discover the function of an internal organ, the objective of this work is to go further in our study and understanding of the relationship between a series of features of dexterity that affect human life.

This research is aimed at contributing to the understanding of dexterity through a scientific analysis of some of its more important features, as well as the development of an accurate, precise and robust method to quantify these characteristics. The methods and procedures developed during this research will be applied to evaluate traditional dexterity assessment methods, comparing dexterity features among tests and hand daily living tasks in order to characterise their reliability and robustness. The study makes use of visual, mathematical, and experimental methods to obtain, process, and analyse a series of hand function parameters that account for some of the main features that affect dexterity in modern daily living.

Despite the specific nature of quantifying features of hand function, the fundamental principles of dexterity assessment often come from the need to analyse medical outcome measures, monitor treatment effectiveness, and the inclusive design of products and services.

Traditionally, dexterity tests have been based upon ordinal scales and are still preferred and widely used in rehabilitation and therapy[1], [3]–[7]. The main limitations of these assessment methods are low reliability and sensitivity and, more importantly, these tests are not robust enough to accurately reflect the patient’s real hand function features and variety of grasping patterns that affect dexterous performance of daily living tasks.

A number of efforts have been made trying to accurately assess hand function, but there are still limitations and gaps when trying to conduct an in-depth evaluation of dexterity. Among such limitations is the lack of conformity to standard metrics, procedures, and analysis of hand function and dexterity.

One of the most widely used dexterity tests is the Purdue Pegboard, mainly for therapy, rehabilitation, and treatment assessment purposes. It was developed by Dr. Joseph Tiffin, an Industrial Psychologist at Purdue University, in 1948 [3], and was originally intended for assessing the dexterity of assembly line workers.

The Purdue Pegboard, like the majority of dexterity test apparatus, measures the quality and the speed of performance of the hand as the person accomplishes a prehensile task.

However, one of the biggest challenges faced by this type of methods is that they tend to be limited to assess only the precision grip, also known as 3-jaw chuck prehension [8].

Colin Light, Paul Chappell and Peter Kyberd made an effort to improve the flexibility of traditional dexterity tests by developing the Southampton Hand Assessment Procedure (SHAP) in 2000 at the University of Southampton [5]. Aiming at the assessment of effectiveness of upper limb prostheses, the SHAP is now applied to general assessments of unimpaired participants. The SHAP consists of 6 abstract tasks and 14 Activities of Daily Living, allowing for the evaluation of a wider range of hand movements focused on grasping ability and limiting the effects of upper limb movement.

Although the SHAP includes its own index of functionality instead of using total time as final score, a number of underlying factors accounting for hand function and particularly dexterity, are still excluded from the assessment.

Moreover, it has been shown that in order to fully understand dexterity and hand movement, an assessment needs to consider the factors that account for quality of movement and efficient solution of motor problems [9]–[11]. It requires measuring of not only time to perform a manipulative task, but also motor coordination and a series of biomechanical parameters, including a kinematic analysis.

The kinematic problem in the human body is commonly addressed as the process of controlling a complex and redundant system via coordinative structures or functional synergies [12]. Many of the techniques most commonly used for kinematic analysis, however, do not allow for the simultaneous measurement of all degrees of freedom and, more importantly, they usually make significant simplifications to measure and analyse the kinematic variables. Furthermore, it is usually desirable that the measuring method does not interfere with the execution of the hand activities. In this sense, the motion tracking of passive markers from video images (Motion Capture) is a good choice, as, although some movement restriction can be introduced by using passive markers, it is much lower than using instrumented gloves or electronic goniometers. It has been widely used in gait analysis, but its application to the hand movement analysis is still scarce. Works found in the literature however, have successfully developed motion capture protocols that allow for the measurement of hand kinematic variables minimising the simplifications and including the majority of the degrees of freedom and range of motion of the hand [12]–[21].

Data acquired through motion capture has been used in different ways to analyse and understand human movement. One of such analysis technique involves the identification of movement synergies from kinematic data. Kinematic synergies or interdependencies have been investigated since the 1980s as a representation of motor control by the nervous system. Representing finger positional data as synergies or coordinated movements is particularly useful when analysing the kinematics of the human hand since it reduces the number of variables and degrees of freedom into a more manageable dimensional space [22]–[25].

Furthermore, it has been shown that natural movements of the hand involve simultaneous and coordinated motion or rotation at multiple joints[26], with evidence that even when healthy subjects are instructed to move one finger, correlated movement occurs in the adjacent fingers [27].

Building on these findings, a number of studies have investigated simultaneous correlated motion at multiple joints to assess hand function from more sophisticated uses of the hand, such as typing [8], playing the piano [28], or haptic interactions [29] by applying principal component analysis, and cross-correlation analysis of finger joint movements.

Kinematic data from motion capture has also been used to quantify movement smoothness as a measure of motor performance of both healthy subjects and people with motor control and musculoskeletal disorders [30]–[32]. Although smoothness metrics have often been based on minimizing jerk, the rate of change of acceleration, [33], many other measures are possible, including three-dimensional curvature, and counting peaks in speed [34]–[37]. Trajectory smoothness has been used to assess individuals with arm ataxia [36], Parkinson's disease [38], children with cerebral palsy [39], and, more generally, it has been shown to have a fundamental role in human basic movement [40], [41].

The relevance of trajectory analysis lies on findings from studies on patients recovering from stroke and other motor related impairments that have revealed a reduction in trajectory smoothness and segmentation of continuous movements [34], [42]. Furthermore, evidence of discrete sub-movements has also been found in the movements of healthy subjects [43], and the decomposition of complex movements into sub-movements has been implemented as analysis tool, as these decomposition of movement has been shown to account for differences in movement quality [44].

This research builds on some of these tools and analysis techniques to test a quantitative assessment of hand motor problem solutions, looking to improve our overall quantification and understanding of dexterity in order to develop more accurate, reliable, and standard methods and metrics.

1.2 Aims and Objectives

The aim of this study is to develop and test a method to assess hand function as one of the fundamental features of dexterity. The method involves quantitative examination and in-depth analysis of kinematic and coordination data. The study is focused on movements required for standard activities of daily living (ADL) and it will be validated through the performance and parallel assessment of a selection of dexterity tests in a lab environment.

To achieve this, the following pieces of equipment and experiments were used and undertaken:

i) Vicon Motion Capture system to obtain instantaneous position of a set of markers on the hand in order to measure and analyse hand and fingers kinematics, examining joint angles, and identifying coordination strategies whilst undertaking ADLs and dexterity tests. Three complimentary analysis techniques were conducted to quantify the spatial, temporal, and coordinative characteristics of the selection of hand movement patterns: trajectory smoothness analysis, cross-correlation analysis of finger interdependencies, and kinematic synergies identification.

ii) Purdue Pegboard test, as gold standard dexterity test, and the Variable Dexterity Test (VDT), a dexterity test developed as part of this research that takes into consideration a variety of grasping patterns. Validity and reliability studies for the VDT were conducted as part of this work.

The relevance of the work lies in the ability of objectively quantify factors that account for dexterity. The resulting data, along with the set of tools and methods used will be further explored for a wide range of applications.

A secondary goal of this research is to determine the validity and accuracy of dexterity tests as methods to assess hand functionality in daily living activities. The new method could be used for the assessment of the inclusiveness of products, the design of new dexterity tests apparatus, hand therapy, rehabilitation, and research in the field of biomechanics.

In order to accomplish the main aims, the study incorporates the following specific objectives and techniques:

i) Identification and classification of standard grasping patterns generally used for activities of daily living.

ii) Exploratory study of existing dexterity tests and their relation with prehensile patterns.

iii) Design and development of a flexible dexterity test taking into account a wide range of grasping patterns and manipulative activities.

iv) Assessment of the validity and reliability of the newly developed dexterity test.

v) Identification of movement coordination strategies through kinematic analysis across a range of activities of daily living (ADL) and dexterity tests.

vi) Assessment of the identified movement coordination patterns as representatives of hand function.

1.3 Scope And Limitation

The scope of this thesis is limited to the incidence of physiological, biomechanical and synergistic function of the hand during activities of daily living. It does not investigate the effect on other parts of the human body, nor does it intend to assess the dynamics and cognition factors of dexterity. Furthermore, the effects of learning and perception on dexterity and hand movement explored in previous works are not part of this investigation.

In this dissertation, the experimental protocols were undertaken on healthy subjects performing activities of daily living involving feeding, packaging interaction, drinking, and dressing. This research is intended as a pilot study on the quantification of hand movement and the size of the sample is not intended to produce normative data. Further research will contribute to the gathering of high-quality normative data for the methods developed and the hand function parameters analysed during this research.

1.4 The Structure of this dissertation

Given the lack of attention in the literature and dexterity's nature as a highly complex psychophysical phenomenon it was impractical to derive a testable hypothesis a-priori. This dissertation has therefore become an exploration of a series of factors that make up dexterity as well as identifying, understanding and quantifying features that will allow the assessment of hand function for a variety of applications. These features were measured and analysed in three experimental studies (Chapter 4). This dissertation is made of six chapters, of which this is the first.

Chapter 2 is a complete literature review on dexterity, object manipulation, assessment of hand function and biomechanical analyses of the hand and fingers, including a review on existing movement assessment technologies and techniques. The importance of the literature review lies on the need for a thorough exploration and identification of existing grip classifications, relevant activities of daily living, methods and technologies, for the design and development of the experimental methodology.

The experimental studies and analyses in chapter 3 and 4 are concerned with manipulative actions involved in interactions between the human hand and objects during standard activities of daily living and dexterity tests. Brief descriptions of each experiment are shown below. Chapter 5 summarises and discusses the findings of this dissertation and suggest possible hypotheses, describing the elements that must be reviewed and work on for future studies to further contribute to the validity and reliability of this work.

Three main studies were conducted, and a dexterity test apparatus was designed and built. Chapter 3 presents the rationale and design of a flexible dexterity test, the Variable Dexterity Test (VDT). It also includes the methods and results of the validity and reliability studies conducted for this newly developed test apparatus.

Chapter 4 describes the kinematic data acquisition method, including the motion capture protocol and the calculation of finger joint angles, as well as the segmentation of manipulative tasks into distinct phases, It then details the analysis of finger movement patterns from joint angles using cross-correlation analysis to explore the differences between specific phases of grasping patterns, The third section of chapter 4 presents a complete description of a finger trajectory analysis study from motion capture data, exploring the idea of manipulative tasks proficiency as a function of finger movement smoothness. Chapter 5 discusses the results and details the relation between the analysed parameters and the definition of dexterity that was established in Chapter 1. The discussion then goes into how each study contributes to our understanding of dexterity and its assessment. The conclusions in Chapter 6 focus on the application and usability of the knowledge produced by this research, as well as potential further research.

Chapter 2

Literature Review

2.1 Introduction

The underlying nature of movement quality, when analyzed by precise scientific methods, has been proved to be a complex and large enterprise that requires collective, organized set of information from a range of sources.

In order to understand and objectively assess the physiological nature of the motor capacity called dexterity this study is focused on quantifying how movements are performed by the human body.

To establish the relation between dexterity and hand function it is important to evaluate movement during the performance of prehensile patterns, ensuring a true reflection of the range and use of hand function during everyday living tasks.

This research aimed to apply various kinematic analysis principles and assessment techniques in order to review and identify the different patters that contribute to proficient performance of ADL's. To this end, contemporary acquisition techniques were explored and reviewed, looking to identify efficient and accurate techniques to collect movement data.

Findings from previous efforts in the subject of hand function and dexterity were reviewed in order to identify and select grasping patterns and related activities of daily living for the experimental section of this study. Furthermore, a review on dexterity tests allowed for the selection of a gold standard test based on frequency of use and existing normative data.

A review on kinematic variables and their previous applications was thoroughly conducted, making particular emphasis on their potential as tools to provide detailed information about movement patterns and their variability. Additionally, the use of such information to aid the identification of the relationships between the diverse range of manipulative movements and movement quality was reviewed.

2.2 Dexterity

The definitions of dexterity through the years have gone from *the ability to manipulate objects with the hands* [1], to *harmonious in movements*, however, as it is explained throughout this work, it is not a skill or a combination of skills. Dexterity can be better explained as a capacity or an ability defining the complex relationship between the nervous system and skills. A person's level of motor dexterity defines how quickly and successfully he or she can develop a certain skill and what level of proficiency he or she is able to reach [2].

Furthermore, factor analysis studies of hand function and dexterity have previously demonstrated that in order to accurately assess someone's level of dexterity, it has to be considered as an ability defined by several factors depending on the task and the activity [9], [45], [46].

Previous efforts to further understand the effect of dexterity on hand-object interactions have identified three main limitations to hand function; cognition, strength and dexterity [47]–[51].

Cognition was defined by Sternberg [52] as a group of mental processes that includes, attention, memory, producing and understanding language, learning, reasoning, problem solving and decision making. However, for purposes of this project, the term will be assumed as "information processing in a participant's or operator's mind or brain" as was defined by Blomberg [53]. The effects of learning and skills acquisition, on the other hand, have been studied and identified as exercisability [2], the development of motor skills through time and experience and the increased ability to solve sudden, unexpected motor problems.

Thus, any manual task or assessment of hand function is affected by experience and learning and the development of new skills and strategies has to be considered in studies of manipulative tasks.

While many studies have been conducted to understand and assess hand strength and the influence of cognition and learning in human-object interactions [54]–[59], the lack of understanding of dexterity and its limitations on manipulative interactions poses a major problem in the development of new hand therapy and rehabilitation methods. Furthermore, in the context of product design, failure to take account of the real hand functional capability of individuals results in people becoming excluded from the use of products and services that are fundamental in quality of life [11], [47], [60]–[62].

The aim of this work is not only to understand dexterity but to develop and test a robust and objective dexterity quantification method that takes into consideration hand kinematics, motor coordination, and grasping patterns, looking to provide researchers and therapists with an applicable understanding of dexterity, its factors, and its limits.

2.3 Anatomy and Physiology of the Hand

In order to understand the problem of assessing dexterity and to better interpret results from the experimental studies of this research it is necessary to understand the basic principles of hand anatomy and physiology, including the anatomical factors that account for a functional hand and finger movement. This section of the literature review will explore such principles, describing the fundamental aspects of the structure of the human hand.

The human hand is a complex prehensile mechanism located at the end of the forearm and consists of five digits and 27 bones, 14 of which are the phalanges (proximal, intermediate and distal) of the fingers. The metacarpal bones connect the fingers and the carpal bones of the wrist. Each human hand has five metacarpals and eight carpal bones.

The carpal bones articulate with the bases of the five metacarpal bones. The heads of the metacarpals articulate with the bases of the respective proximal phalanx of the fingers and the thumb.

The articulation between the metacarpal bones and the carpal bones, forms the carpometacarpal joints that allow flexion/extension movements and radial and ulnar deviation. Independent movement at these joints is limited in digits 2 to 4, with the thumb having greater independence, making the thumb capable of flexion/extension, abduction/adduction, and opposition at this joint [63].

Digits 2 to 4 have three bones known as proximal, middle, and distal phalanges, and each one of these fingers has three joints (Figure 2.1), the metacarpophalangeal (MCP), the proximal interphalangeal (PIP), and the distal interphalangeal (DIP) joints. The thumb has only two phalanges, proximal and distal, and two joints, MCP and interphalangeal (IP) joints. Interphalangeal joints are hinge joints capable of only flexion and extension (one degree of freedom), while the MCP joints, commonly known as knuckles, and generally characterised as universal or saddle joints, are capable of flexion/extension and abduction/adduction movements (movements away from and toward the median plane of the hand). Unlike other primates, humans' distal interphalangeal joints are capable of passive extension beyond 30°, while PIP joints don't allow passive extension beyond 0°. With the exception of the thumb, the index finger has the greatest range of abduction/adduction movements at 30° [64], [65].

The sum of active flexion (joint moved voluntarily by the subject) at the MCP, PIP, and DIP joints on each finger is known as the total active range of motion and The American Society for Surgery of the Hand has reported it to be 260° for a typical healthy finger. Of those 260°, 85° correspond to the MCP, 110° to the PIP, and 65° to the DIP joints [66], [67].

Reported values for range of active extension at the MCP joint varies between individuals, but has been reported to reach 30–40° [68], [69], while studies have shown that both passive and active MCP flexion as well total active range of motion tend to increase linearly from the index to the little finger [65], [70].

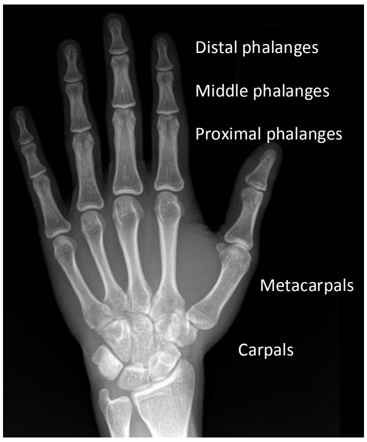


FIGURE 2.1 GROUPS OF BONES OF THE HAND

The movements of the hand are controlled by 29 muscles, some of which are split into separate tendons to reach distal parts of the hand. When taking into account this subdivisions, the number of muscles controlling the hand increases to 38 [71], [72].

Hand muscles are classified as extrinsic and intrinsic muscles. The extrinsic muscles originate in the forearm and are made of long flexor and extensor muscles of the wrist and fingers. As they approach the wrist the muscle bellies are replaced by tendons, and pass through the carpal tunnel to reach the fingers [68].

Examples of extrinsic flexor muscles are the flexor pollicis longus in charge of flexing the IP joint of the thumb, the flexor digitorum profundus that flexes the DIP joint of digits 2-4, and the flexor digitorum superficialis that flexes the PIP of digits 2-4. The flexor carpi ulnaris and flexor carpi radialis are in charge of flexing the wrist.

The extensor muscles originate from the ulna and extend through the dorsal aspect of the forearm, passing through the dorsal carpal ligament at the wrist where they are split into extensor tendons and arranged into six dorsal tendon compartments, reaching the MCP and IP joints of the fingers.

The intrinsic muscles originate and insert within the hand and are subdivided as the thenar, hypothenar, interosseous, and lumbrical groups.

The thenar muscles (the abductor pollicis brevis, opponens pollicis, and flexor pollicis brevis) are in charge of the thumb metacarpal and are involved in pronating and opposing the thumb. The hypothenar muscles (abductor digiti minimi, flexor digiti minimi, and opponens digiti minimi) abduct and flex the little finger, while the lumbrical and interosseous muscles flex the MP joints, extend the IP joints of the fingers, and adduct and abduct the fingers [67], [72].

The muscles of the hand are innervated by the radial, median, and ulnar nerves. The radial nerve innervates the finger extensors and the thumb abductor, the muscles that extend the wrist and metacarpophalangeal joints and that abduct and extend the thumb. The median nerve is mostly involved in the flexion of the wrist and fingers and the opposition of the thumb, while the he ulnar nerve innervates all other intrinsic muscles of the hand.

The radial, ulnar, and medial nerves are also involved in the sensory innervation of the hand The radial nerve supplies sensibility to the radial three quarters of the dorsum of the hand (opposite to the palm), the dorsal surface of the thumb, index and middle fingers, and the radial half of the ring finger. The median nerve innervates the volar (same side as the palm) surfaces of the thumb, index, and middle fingers and the radial side of the ring finger, with dorsal branches of the nerve reaching the dorsal aspect of the index and middle fingers distal to the PIP joint and the radial half of the ring finger. The little finger and the ulnar section of the ring on the palmar surface are innervated by the ulnar nerve, as well as the dorsal aspect of the hand over the ring and little finger metacarpals, the dorsum of the little finger, and the dorso-ulnar half of the ring finger [66], [67].

Additionally, the median nerve plays a fundamental role in hand manipulative tasks, since it innervates and carries information from a large area of skin on the palm of the hand, and innervates the intrinsic muscles controlling the characteristic movements of the thumb when handling objects [67], [73].

2.4 Learning to grasp

The dexterous manipulation of objects involves reaching and grasping an object, transporting the hand, forming the grasping pattern, and getting control of the object to complete a task [67], [74]. Transporting the had to the location of the object involves the interpretation of space and environment, regulating velocity and acceleration as the hand reduces its distance with the object. The interpretation of spatial parameters continues as the grip starts to take form, taking information from the object such as size, shape, and spatial configuration throughout the task [74]–[76].

This highly coordinated process is supported and controlled by a complex integration of sensorial and empirical information with motor coordination, allowing the system to continuously adapt to sudden changes and produce efficient responses in order to acquire stable control of the object [58], [74], [77].

The sensorimotor system that allows grasping objects has been shown to develop gradually, from a basic, unskillful form in newborns to a well-coordinated and refined process in adults, with studies by Konczack and Dichgans, von Hofsten, and Schneiberg [59], [78], [79] suggesting that the acquisition of an optimal coordination of the reaching and grasping commands is reached only around 12 years of age, and is dependent on three conditions: refinement of reaching, improvement of grip formation, and decrease on the dependence on visual guidance.

Schneiberg et al. [79] characterised the development of coordination during reaching in children over the age of 3 years and identified age ranges in which stable patterns emerge by studying children reaching from a seated position with the dominant arm and grasping an object at different distances. They acquired kinematic data from markers placed on the arm, head and trunk and found smoother hand and arm trajectories as age increased, rendering evidence of some of the characteristics of mature movement patterns. Additionally, their results provided evidence of the variability in the rates of development of different aspects of movement.

The three conditions previously identified as fundamental for a development of optimal grasping are greatly influenced by the physical development of the hand, the effects of maturation of the central nervous system, and experience and repetition interacting with objects.

The anatomical features of the hand are well defined at 10 weeks' gestation, and a first, undeveloped grasp reflex in response to contact across the palm has been seen two weeks later. The size of the limbs increases gradually with age, reaching a growing factor of up to 300% by the age of 18 years. These changes in hand size greatly influence the manipulative abilities, as interactions with objects of different sizes and shapes become more natural [67], [80].

The ability to extend the arms and reach for objects develops from birth, with studies by Hofsten showing neonates are capable of moving their arms toward an object and bring their hands into their field of view [59]. These primitive reaching movements are characterised by extension of the fingers as the arm extends, suggesting a level of interdependence. Hofsten also found that in some of these primitive movements, there is a significant decrease of hand velocity as it approaches the object, even though the hand rarely makes contact with the object. In a further analysis of these undeveloped movements, Hofsten found that these primitive reaching movements tend to be less frequent and reach a minimum frequency about 7 weeks of age. After this minimum, he observed a sudden increase of these movements, coupled with a changed hand posture. The infants tended to make a fist as the arm extended, suggesting an increased independence of arm and fingers. This development process continues until the infant is able to reach and grasp an object [58], [59].

The evolution of reaching movements continues with the development of the palmar grasp, identified as the earliest grasping pattern, along with an improved control of hand orientation according to the position of the object [58], [59], [67], [79]. Infants have been shown to be able to grasp as the hand makes contact with the object at about 3-5 months of age, and by 6–7 months they are able to anticipate contact and start flexing fingers as the hand approaches the object, showing coordinated response to visual cues to perform and control the formation of the grasp. This development of anticipation of contact with the object was observed by Hofsten et al. by tracking the position of the index and thumb of infants as they reached for abstract objects. In this study, 75% of grasps performed by 5-6 month-old infants occurred within 100 ms before making contact with the object [59].

The integration of reaching and grasping gets more consistent as infants reach the first year of age, with the first signs of adjustment to object size during reaching observed at this age. However, the lack of visual cues and experience perceiving object sizes and shapes contribute to the hand aperture not being accurately scaled to object size. Studies by Hofsten have shown that younger infants consistently perform larger finger extension than older children for objects of different sizes [81].

Kuhtz-Buschbeck et al. [58], [82] conducted a cross-sectional study of 4 to 12 year old children and found a tighter association between grip formation and reaching, as well as greater uniformity of movements in older children. Furthermore, their study revealed reaching was less dependent on visual feedback in older children, with 12-year old participants efficiently adjusting the grasping pattern to object size even without visual feedback.

These three characteristics define well-developed grasping skills and suggest experience and practice of manipulative tasks allow for a more integrated reach and grasp process. Moreover, the efficient use of visual cues to plan and choose a grasping pattern is significantly improved with age, suggesting not only a more developed sensorimotor system, but also a deeper understanding and knowledge of the effects of object size, shape, and orientation.

The study of the relation between motor and cognitive development in infancy has produced fundamental insights to our overall understanding of prehension and dexterous manipulation of objects, understanding how the development of cognitive capacity influences both the acquisition of information from the environment and the use of such information to interact with objects.

The sequential development of grasping skills from neo-natal grasping, through grasping after contact with an object, to visually guided grasping strategies is a continuous process that keeps evolving with experience and practice, allowing humans to acquire new skills and proficiency in the performance of a variety of tasks. Furthermore, the process enables humans to adapt to declines in performance with increasing age, developing coping strategies to deal with a less efficient sensorimotor system.

In the experimental studies of this research, kinematic data from healthy adults performing activities of daily living and dexterity tests may provide further evidence of the effects of object size, familiarity, and nature of the task to the process of selection and performance of grasping patterns.

2.5 Grasping patterns

The first step in understanding the relationship between dexterity and hand-object interaction is to identify how objects are gripped and manipulated, understanding the interface between the human body and the object.

Research on grasping has focused on the intrinsic properties of an object, the dynamics of grip, and the effects of task constraints and goals on the stable manipulation of objects [67], [69], [73], and a huge amount of work has been aimed at classifying human grip styles using various different methods and parameters. However, there is an infinite variety of possible grasping patterns and, for purposes of analysis, this work will focus in distinguishing the most common classifications and grasping patterns from the literature.

In one of the first efforts to standardise a classification of grasping patters, Napier [83] concluded that the movements of the hand can be classified into two groups: 1) Prehensile movements, or movements in which the object is held partly or completely within the hand; and 2) non-prehensile movements, or movements in which there is no grasping involved and objects are manipulated by pushing of lifting either by the complete hand or by individual fingers.

From what he called prehensile movements of the hand, Napier came to the conclusion that there are two distinct patterns of movement to achieve stability depending on the intended activity: power grip and precision grip.

In the precision grip the object is held between the flexor aspects of fingers and the opposing thumb, while in the power grip the object may be held in a clamp formed by the partly flexed fingers and the palm, with the thumb applying counter pressure in the palm of the hand.

What Napier's work states is that objects with the same shape can be used in different ways, according to the power or precision required for the activity. Thus, a vast range of intended actions involving objects of all shapes and sizes during activities of daily life can be determined from these two main grasping patterns. This classification by Napier, however, did not attempt go deep into the variability within these two main patterns, and, furthermore, it did not provide an understanding of the roles of individual fingers and their effects on object stability, strength, and pressure during manipulative tasks.

Taylor and Schwartz [63] realised that object-contact patterns provide a satisfactory basis for an objective grip classification. From an observational study of natural grip styles used when picking up and holding for use objects in activities of daily living, and using as a reference a previous classification by Schlesinger [84], they identified three main grip styles: palmar, tip and lateral. In their observational study, they investigated the frequency of use of the selected grip styles during daily living tasks. Finally, they conducted a study on hand movements and its associated dynamics to conclude that hand function depends not only on the structural arrangement but also on a complex automatic system of control, introducing concepts that were later become the basis of contemporary studies of hand function, and expanding their initial three grip classification to six grips: lateral, spherical, tip, cylinder, and pulp (Figure 2.2).

Considering that, for specific applications, a more detailed classification is necessary, Kamakura et al. built on these previous findings and worked on the idea that normal adults use of specific grasping patterns depends not only on the shape of the object and the intended activity, but also the person's habits, and, many times, chance [85], adding complexity to the problem and, at the same time, introducing concepts that had not been explored, such as perception, decision making, and learning.

In Kamakura's study, the characteristics of common patterns are determined mainly by the position of the fingers. The contact areas were considered key to identifying these patterns, but, as he emphasised, contact areas are not necessarily the same as the pressure areas.

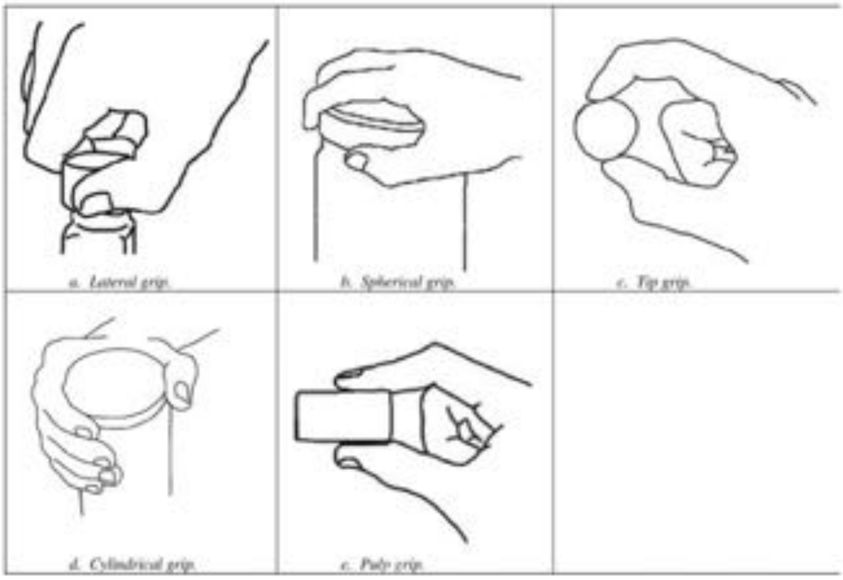


FIGURE 2.2 TAYLOR AND SCHWARTZ GRIP CLASSIFICATION

In Kamakura's work, the role of fingers was analysed not only for pressure and strength, but also for optimal control of the object, balance, and strategy.

Kamakura produced a wider classification based on 4 major categories with information from Napier's work on the prehension of 98 common objects. The 4 categories identified from position of fingers and contact areas were:

a) Power Grip: named after Napier's classification, wide area of the hand, including the palm, makes contact with the object. Contact areas of the fingers are on the volar side.
b) Intermediate Grip: intermediate position between Power and Precision Grips. The palm is no longer included and the fingers are moderately flexed. Contact areas include the radial aspect of the index or the middle finger.

c) Precision Grip: the object is held between the volar aspects of the fingers and the pulp of the thumb.
d) Grip involving no thumb: used for small light objects held between adjacent fingers.

From these main categories, Kamakura found 14 grip styles, similar in most parameters to the ones identified in previous works by Taylor and Schwarz, although giving greater importance to the fingers' contact areas and the person's habits as factors influencing grasping patterns.

Kamakura identified what he called the 3-jaw chuck prehension, or precision grip, as the primary pattern that separates humans from primates. According to Kamakura it is this pattern that allows humans to complete most precision tasks, using a combination of thumb and fingers without the need of using the palm. With the 3-jaw-chuck hand pattern humans perform such tasks as writing, buttoning, and tying laces.

Kamakura's conclusions allowed for further understanding of the factors involved in grasping and object manipulation, however, his classification still lacked the support of normative data from a significant sample, and it was yet to be fully understood the frequency with which humans perform any given grip style.

In her anthropology studies, Marzke [73] took into account the relationships between precision gripping, tool behaviors, and hand morphology in modern hominoids, finding evidence of the influence of the thumb and its movements during precision grips in complex human activities such as tool making. Marzke's studies noted the importance of the precision grip, as well as the role of the opposition movement of the thumb, in the development of human's habits and tools, further confirming the main classification developed by Napier and Schwartz, and emphasizing the role of individual fingers during manipulative tasks.

Following these series of seminal works on grasp taxonomy, the general characteristic of grip classifications remained largely consistent, and it has been used for nomenclature, standardisation, and characterisation of research studies across varios disciplines and applications: pinch or precision, cylinder or power, spherical, and extension grip styles (Figure 2.3).

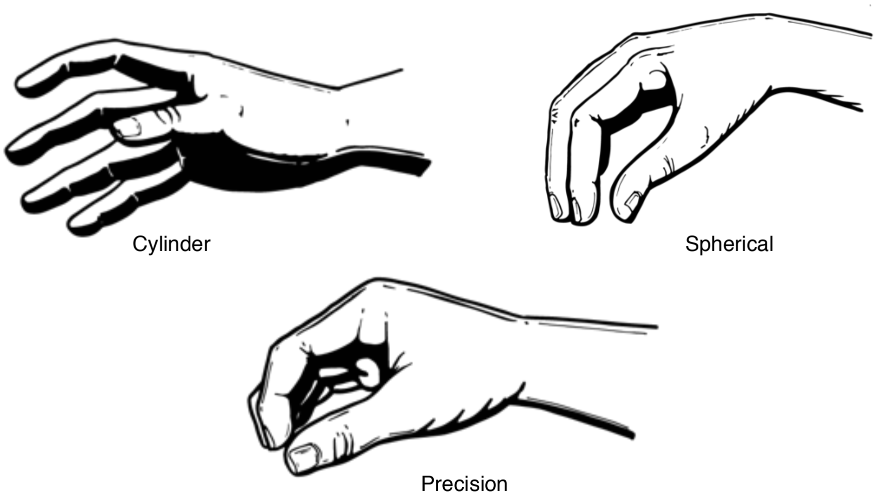


FIGURE 2.3 GRIP STYLES GENERAL CLASSIFICATION

In order to relate the anatomical study of grip styles with quality of hand function, several studies have been conducted trying to establish tools and normative data looking to improve the understanding of the factos accounting for proficient object manipulation and the role of finger position on these factors.

Light [5] worked on a new assessment procedure to obtain hand function results in a clinical environment, taking into consideration distinct functional positions of the hand during activities of daily living. The goal of this investigation was to produce an Index of Functionality that reflected the prehension patterns that are fundamental to the activity in order to evaluate prosthesis.

Light linked the hand's ability to form a natural and optimal grip to dexterity and considered this to be determinant in the speed of task, concluding that time taken to complete a task will be strongly related with hand function. Light's efforts provided fundamental information on the relation between grasping patterns and daily living tasks, and expanded the approach to hand function from traditional dexterity tests to a more flexible and robust assessment.

Looking to further investigate the role of finger opposition into the performance of grasping patterns, Iberall [86] studied three basic methods of applying oppositions around objects and worked on a classification of postures of standard prehensile patterns based on this concept. In his work, Iberall introduced the idea that hand postures are not discrete as most classifications suggest, adding that there is always more than one type of of grip being used at a time.

Iberall's oppositions approach is based on the principle of virtual fingers, in which a virtual finger is defined as one or more fingers being used as opposition and/or support during prehension. His work produced some of the first conclusions on the role of fingers that are not necessarily in direct contact with the object, and the variability of grasping patterns throughout the duration of the manipulative task.

The three basic methods of opposition identified by Iberall are:

a) Pad opposition: between the thumb pad (virtual finger 1) and the finger pads (virtual finger 2) along an axis parallel to the palm. Sacrifices stability and maximum force in favor of greater flexibility.
b) Palm opposition: between the palm (virtual finger 1) and the digits (virtual finger 2), offers greater stability at the expense of flexibility.
c) Side opposition: either between the thumb (virtual finger 1) and the side of the index finger (virtual finger 2), or else between the sides of the fingers, offers flexibility and stability equally.

Based on these methods of opposition, and with information provided by alternative studies on the subject like Napier's and Schwarz', Iberall conlcuded on a classification of human grip based on six main postures: basic power (cylinder/palm opposition), basic precision (palm, pad and side opposition), basic precision/power (palm and pad opposition), modified power (palm opposition), modified precision/power (palm and side opposition), and fortified precision/power (palm and pad opposition). This classificaiton can be seen as an extended version of the general classification, sub-dividing the precision, cylinder, and spherical grip styles according to the position of the thumb and the palm.

Studies by Yoxall et al. [47] built on Iberall's findings by investigating user-packaging interactions, considering not only grip styles but also strenght measurement and numerical models of the hand. In his work, Yoxall conducted an ethnography study to identify grip types and postures during packaging interaction. The observed grip patterns were compared to those identified by Taylor and Schwarz and new types were found during testing and video observation while subjects tried to open packages involving pinch, grab and pull actions. Conclusions from Yoxall's work were in line with Iberall's concept of continuous grasping patterns that vary according to the stage of the task.

In one of the most recent efforts to further standardise and classify grasping patterns, Feix et al. [87] built on conclusions from Iberall's work on opposition and virtual finger and analysed and compared existing human grasp taxonomies, synthesising them into a single new taxonomy, "The GRASP Taxonomy" (Figure 2.4) after a project funded by the European Commission. Feix et al. considered only static and stable grasps performed by one hand, identifying and classifying one of the largest set of different grip styles from previous works.

Overall, 33 different grasp types were found and arranged into the GRASP taxonomy. Within the taxonomy, grasps were arranged according to 1) opposition type, 2) the virtual finger assignments (when several fingers work together as a functional unit), 3) type in terms of power, precision, or intermediate grasp, and 4) the position of the thumb.

The resulting taxonomy succeeded in standardising a definition for grasp and incorporating and building on all grasps from previous studies. Feix el at. emphasised the need for a compilation of statistics of human hand use from past works, although acknowledging the difficulty in comparing previous publications, due to the diversity of defined grip types and factors defining grasping patterns.

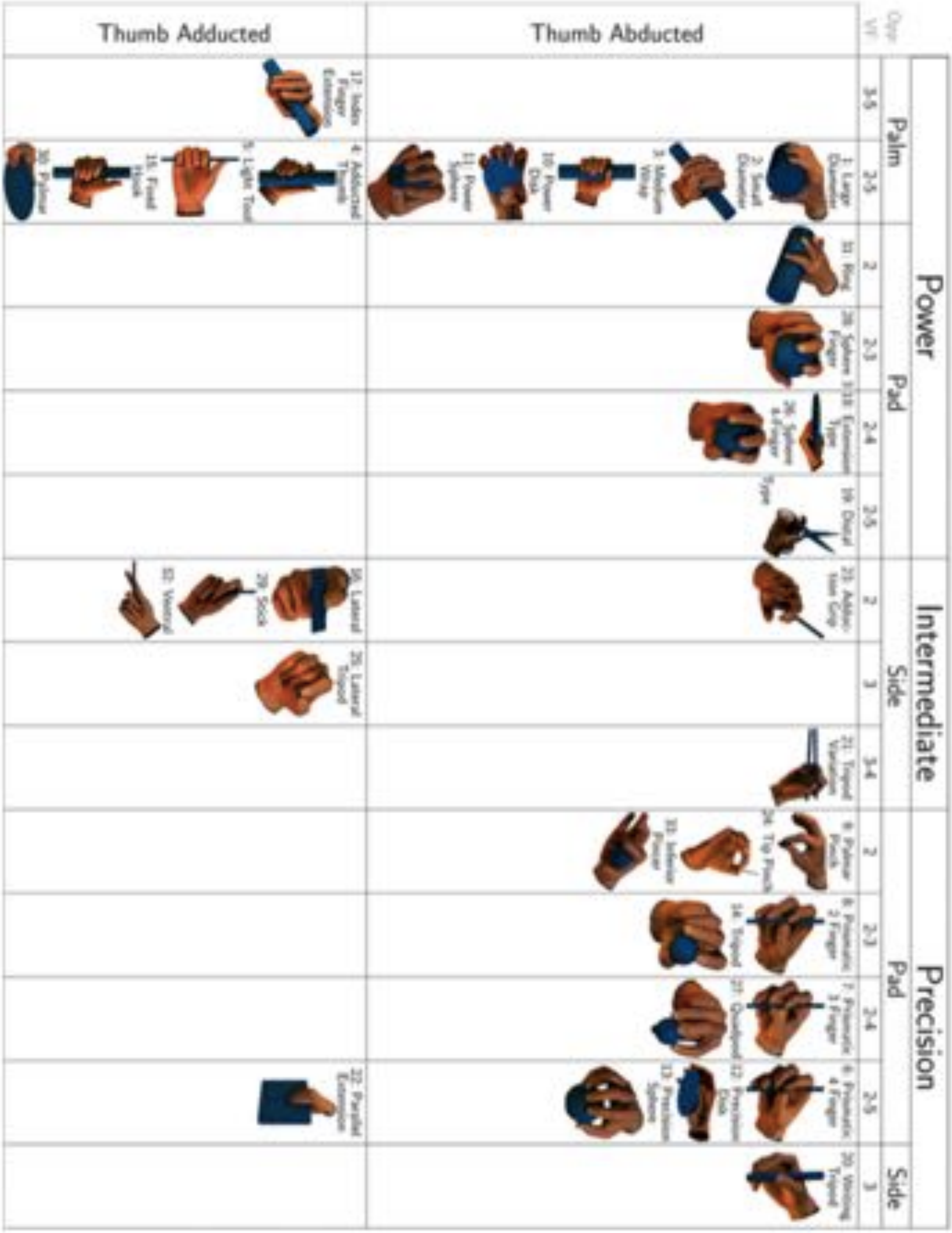


FIGURE 2.4 GRASP TAXONOMY INCORPORATING PREVIOUS GRASP CLASSIFICATIONS. IST-FP7-IP-215821 (C) GRASP 2008-2012. ALL RIGHTS RESERVED. GRASP IS FUNDED BY THE EUROPEAN COMMISSION THOUGH THE COGNITION UNIT, INFORMATION SOCIETY AND MEDIA DG

Aiming to fill the gap highlighted by previous classifications, Bullock et al. [88] studied the frequency of use of pehensile human hand movements during activities of daily lving by observing housekeepers and machinists. A head-mounted camera was used to record 8 hours per day of hand usage for every selected subject. Duration and frequency of use were recorded for every grip style identified from Taylor's grip classification and Feix et al. Their study showed a greater diversity of patterns from machinists when compared to housekeepers, and resulted in a list of 10 most frequently used grips as seen in Table 2.1. Data from this study provided fundamental information on grasping patterns previously identified and classified, with precision and cylinder grips having the highest frequency of use across both housekeepers and machinists.

TABLE 2.1 TOP 10 GRIP STYLES FROM BULLOCK'S FREQUENCY STUDY. THE STYLES SELECTED FOR THE EXPERIMENTAL STUDIES OF THIS RESEARCH ARE IN BOLD. LATERAL, TRIPOD AND DISK WILL BE ASSESSED AS PRECISION GRIP, WHILE CYLINDER AND SPHERICAL GRIP WILL REPRESENT GROSSER PATTERNS.

Grasp	Duration proportion (%)	Frequency (%)	Mean duration per grasp (s)
Medium wrap/Cylinder	23 ± 2	14.0 ± 0.5	12
Precision disk	17 ± 1	8.2 ± 0.4	19
Lateral pinch	7 ± 1	9 ± 2	4.5
Tripod/Precision	6.4 ± 0.5	7.4 ± 0.5	4.8
Lateral tripod	5.3 ± 0.4	8 ± 1	3.3
Spherical	4.6 ± 0.4	7 ± 0.5	5.1
Thumb-2 finger	4.5 ± 0.3	5.5 ± 0.4	4.3
Index finger extension	5.6 ± 0.5	3.6 ± 0.2	11
Light tool	3.7 ± 0.4	4.3 ± 0.2	5.0
Thumb-3 finger	3.7 ± 0.4	4.0 ± 0.4	5.4

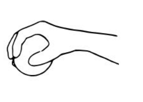
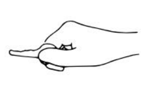
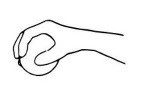
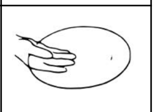
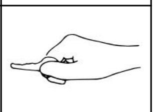
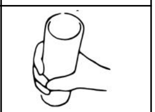
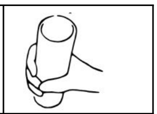
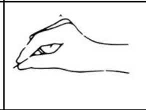
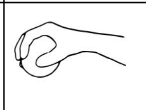
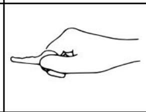
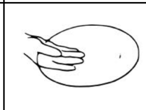
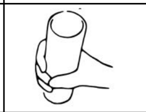
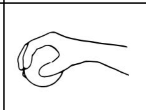
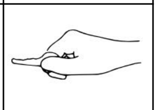
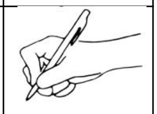
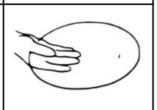
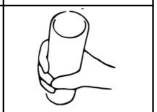
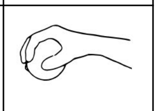
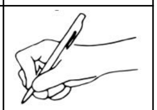
A second conclusion from this study was that the frequency of use of any grasping pattern is greatly affected by the environment (objects' size, weight, rigidity, force requirements, task) and that frequency data has the potential of providing important estimates of human hand use. These findings allowed a deeper understanding of manipulation strategies and the principles behind the selection of grasping pattern.

Additionally, the study showed that variations of the precision and power grips tend to trade off with each other, depending on the requirements of strength and precision of the task and the object.

Further investigation on the relationships between different grasps and object types, as well as the effects of experience in the choice of graspin patterns coupled with the kinematic characterisation of finger movements may contribute to the findings from this work.

Although this research will be based on kinematic analyses of manipulative tasks and is not inteded to fully assess the cognition and learning factors involved in dexterous movements, the identification of movement patterns and their variability across tasks and subjects will allow further discussion on the role of individual fingers, object shape, familiarity, and learning in proficient object manipulation. Moreover, the experimental studies will build on previously identified grasping patterns mentioned in this review (Table 2.2) in an effort to enhance our characterisation of the most commonly used grasping patterns according to Bullock et al. and Iberall et al. The selection of patterns for the experimental studies of this research will include the cylinder grip and the spherical grip as representatives of grosser patterns, and the precision grip varieties as representative of finer grasping patterns.

TABLE 2.2 SUMMARY OF REVIEWED GRASPING PATTERNS CLASSIFICATIONS. THE PRECISION, CYLINDER, AND SPHERICAL GRASPING PATTERNS HAVE BEEN CONSTANTLY INCLUDED IN MOST RELEVANT STUDIES.

Authors	Year	Grasping patterns	
Schlesinger	1919	Power	
		Precision	
		Spherical	
		Lateral	
Taylor and Schwartz	1955	Cylindrical	
		Spherical	
		Tip	
		Palmar	
		Lateral	
Napier	1956	Precision	
		Power	
Kamakura et al.	1980	Power	
		Precision	
		Spherical	
		Lateral	
		Extension	
Light et al.	1999	Power	
		Spherical	
		Lateral	
		Tripod	
		Extension	
		Tip	
Feix et al.	2008	Power/Cylindrical	
		Power/Spherical	
		Intermediate	
		Precision	

2.6 Traditional Dexterity Tests

Hand therapists, physicians, and human movement researchers from a wide range of fields have developed and used many tests and apparatus with the general aim to describe the hand's ability to form a natural and optimal grip, as indicative of the level of dexterity during manual activities.

However, there is no one individual variable that can define and encompass hand functional ability, and it has been proved that in order to accurately measure hand function, a valid test must take into account dynamics and perception of movement, speed of manipulation and their relationship to functional tasks [9]. For this reason, many tests have been designed to use time as the critical measure of performance, providing a clinically meaningful deduction from the measurement.

Choosing the most appropriate assessment method, and having a clear understanding of the strengths and limitations of each test is important in both clinical and research environments. Using appropriate, valid and reliable tests can improve the quality of the resulting data, helping to achieve a better understanding of how disease progresses, the level of structural impairment and how this impacts on the individual's function and quality of life. Nevertheless, published data and practical information on reliability and validity for many hand function tests is still limited for both clinicians and researchers [89].

Examples of commonly used timed tests in the occupational therapy and rehabilitation fields are the Jebsen Hand Function Test [90], the Purdue Pegboard Test [3] (Figure 2.5), the Minnesota Manual Dexterity Test [4], and the Functional Dexterity Test (FDT) [1]. All of these tests use the same basic principle of standardized objects (such as pegs or blocks) as test items to determine the person's hand function while using their fingers to accomplish tasks. A detailed list of relevant dexterity tests can be found on Table 2.3.

The Purdue Pegboard Test [3] (Figure 2.5) was developed in 1948 to assess the dexterity of assembly line workers and it measures the ability to make skilful controlled hand manipulations of small objects. The subject is provided with a pegboard having two rows of small holes (25 holes in each row) and four small cups containing pegs, washers, or collars. The patient is then required to pick up one peg at a time and place it in a hole as rapidly as possible with the right hand throughout a 30 second trial. The final dexterity score is the number of pegs correctly placed. The test can be repeated for the non-dominant hand and for both hands at the same time. In addition, it includes an assembly subtest that requires the subject to put together washers, collars and pegs in a specified order and into the holes.

Although initially thought to be used for the selection of employees for jobs requiring dexterity and coordination, this device has been used extensively for many testing applications, such as Physical Therapy, Occupational Therapy, Vocational Evaluation, and Pre-employment Screening.

TABLE 2.3 OVERVIEW OF TESTS IDENTIFIED

Hand Function Assessment	Reference	Description	Main Outcome	Advantages	Limitations
Purdue Pegborad Test	Tiffin, 1948 [3]	• Measures the ability to make hand manipulations of small objects. • Consists of a pegboard with two rows of small holes (25 holes in each row) and four small cups containing pegs, washers, or collars.	Number of pegs correctly placed after 30 seconds.	Significant amount of reliability and validity studies. Normative data available from a range of populations [91]–[93]	- Originally designed as a tool for the selection of employees. - Only measures ability to manipulate small objects (precision grip).
Jebsen Test	Jebsen, 1969 [90]	• Measures broad aspects of hand function in activities of daily living using standardized tasks. • Consists of 7 tasks: writing, page turning, picking up small objects, simulated feeding, stacking checkers, picking up large light cans, picking up large heavy cans.	Time taken to complete each task.	- Established inter-rater and test-re-test reliability [90], [93]. - Has been used across populations and conditions [90]. - Measures a range of grasping patterns.	- Validity needs further testing [9], [90], [93]. - The test Is based on familiar activities of daily living, subject to the effects of learning and prejudice [5].
Minnesota Dexterity Test	Surrey, et al., 2003 [4]	• Measures the ability to make skilful controlled arm-hand manipulations of larger objects • There are two versions of the test: Minnesota Rate of Manipulation Test and Minnesota	Time taken to complete the task.	The test has been used to produce data from a range of populations and conditions [4], [93].	- Lack of relevant validity and reliability studies with the latest version of the test [4]. - Information from the test is limited to power grip.

		(MRMT), and Minnesota Manual Dexterity Test (MMDT), both utilize the same manual and norms. • MRMT uses wooden board and blocks, MMDT uses plastic board and blocks.			
Sollerman Hand Function Test	Sollerman, Ejeskar, 1995 [94]	• The test consists of 20 tasks representative of 8 grasping patterns. • Tasks are related to activities of daily living. • Grasping patterns are 4 variations of the precision grip and 2 variations of spherical and cylinder grip	Each task is scored by an examiner in a scale from 4 - 0 according to standard guidelines	Provides information about a range of grasping patterns.	- Needs further testing for validity and reliability [94]. - Based around ADLs, may be subject to effects of familiarity. - Score is based on assessor's rating and may be subject to variability in large longitudinal studies.
Functional Dexterity Test	Aaron, Jansen, 1992 [1]	• Designed to assess performance of precision grip • The test is made of a pegboard and 16 pegs • The patient is asked to turn over all the pegs on the pegboard.	Time taken to complete the task	Specifically designed for clinical use. Normative data have been collected in studies with a range of ages, skills, and conditions [1].	Needs further validity and reliability studies [1]. Only provides information about precision grip.
Southampton Hand Assessment Procedure	Light et al., 2002 [5]	• Designed for the assessment of 6 grasping patterns: tripod, tip, lateral, power, spherical, and extension grips. • Consists of 6 abstract tasks and 14 activities of daily living.	Overall Index of functionality based on self-timed tasks	- Provides information about a range of grasping patterns. - Combines familiar ADLs with abstract tasks, reducing effects of learning. - Use of self-timed	- Needs further validity and reliability studies. - Needs larger normative data across populations (age, conditions, skills)

				technique reduces assessor’s error. - Index of functionality better incorporates performance results across patterns.	

Due to its longevity and its wide range of applications, the Purdue Pegboard Test has been used to produce a large number of normative data, validity and reliability studies for specific populations both healthy and impaired [92].

FIGURE 2.5 PURDUE PEGBOARD TEST, AN EXAMPLE OF TRADITIONAL HAND FUNCTION TIMED TESTS.

Moreover, it has been ranked by systematic reviews as one of the top three assessments of dexterity for health care professionals, due to its reliability and validity as well as its fewer confounding variables, such as age, gender, and handedness [92], [93].

The Minnesota Manual Dexterity (MMD) and the Functional Dexterity (FDT) tests were designed to fill some of the gaps of dexterity assessment methods in the occupational therapy and rehabilitation fields, in particular, they were designed to measure a specific grasping pattern.

The FDT, by Aaron and Jansen [1], is one of the first examples of a hand function test developed to focus specifically on one specific grasping pattern, the precision grip. Unlike the Purdue Pegboard, the FDT was originally designed and built to provide clinicians with a time-efficient assessment tool that provides information regarding the patient’s ability to use the hand for functional tasks requiring the precision grasping pattern. The FDT, however lacks the amount of normative data and validity studies of the Purdue Pegboard and has not been as widely used [1], [92], [93].

The MMD was designed to measure the ability to make skilful controlled arm-hand manipulations of larger objects, specifically, the power and spherical grips. There are two versions of the test: Minnesota Rate of Manipulation Test and Minnesota (MRMT), and Minnesota Manual Dexterity Test (MMDT), both utilize the same manual and norms [4]. The MRMT uses wooden board and blocks, while the MMDT is an updated version of the test and uses plastic board and blocks. Both versions require patients to place and turn cylindrical blocks into holes on a board, with the time taken to complete the test being the score. The MRMT was intended to be an example of a standardized test for gross coordination and dexterity, and it has been used to produce a large amount of normative data as well as validity and reliability studies [4], [95].

Studies assessing the reliability of the MRMT have contradictory conclusions; Baxter-Petralia et al. [96] conducted a thorough investigation on the MRMT and listed several advantages and disadvantages of the test. They found an advantage in the possibility of evaluating endurance during manipulation if many of the subtests are administered during one evaluation period, while, on the other hand, the main limitation according to their study was that the test provides information about only one type of hand manipulation skill, the power grip. Furthermore, they found that distal function may not be measured accurately if proximal range of motion limitations are present [96].

The above-mentioned procedures are focused on the assessment of an individual grasping pattern, and, although there is statistical evidence of their reliability and validity, as well as a number of studies providing normative data, they are all still limited when trying to measure a wider range of patterns required for daily living tasks.

Aiming to close the gap between daily living tasks and hand function assessment procedures Light et al. [5] developed the Southampton Hand Assessment Procedure (SHAP), designed to allow objective results of hand function for application in health practice from the assessment of 6 grasping patterns: tripod, tip, lateral, power, spherical, and extension grips.

A second aim of the SHAP was to provide uniformity and standardisation among assessment procedures and resulting data for both natural and prosthetic hands. Light et al. found that one of the reasons behind this lack of uniformity is the use of evaluators' ratings to measure hand function, since such ratings tend to present a significant variability in large and global sets of data collection.

The SHAP consists of 6 abstract tasks and 14 activities of daily living (Table 2.4), combining typical clinical assessment techniques, that are made of a series of ADLs, with traditional abstract board tests. The abstract test section of the SHAP reduces familiarity and the learning effect of patients, while at the same time leading participants to perform specific grasping patterns determined by object shape. In order to avoid variability due to subjective time measured assessment the SHAP uses a self-timed technique. Furthermore, unlike most tests, the final score is not measured time but an overall Index of functionality that integrates results from the 6 evaluated grasping patterns.

TABLE 2.4 ABSTRACT TASKS AND ADLS INCLUDED IN THE SOUTHAMPTON HAND ASSESSMENT PROCEDURE

Abstract tasks	
No.	**Task**
1	Spherical
2	Tripod
3	Power
4	Lateral
5	Tip
6	Extension

Activities of daily living	
No.	**Task**
7	Pick up coin
8	Button board
9	Simulated food cutting
10	Page turning
11	Jar lid
12	Glass jug pouring
13	Carton pouring
14	Lifting a heavy object
15	Lifting a light object
16	Lifting a tray
17	Rotate key
18	Open/Close zip
19	Rotate a screw
20	Door handle

Reliability studies showed the SHAP is reliable, with statistically insignificant differences between subjects' during replicate trials and good inter-rater repeatability. Validity was not tested against a benchmark, and normal hand function data was established through a study involving a control group of 24 healthy individuals [5].

In this research, an effort will be made to build on findings and gaps from these assessment methods, aiming to cover the spectrum of grasping patterns explored in the previous section of this review. The quantification of the characteristics of the main grasping patterns will help to further understand the different hand functional requirements of daily living tasks, while providing insight on factors such as movement strategies, object stability, and the phases of manipulative tasks.

The Purdue Pegboard Test will be used as benchmark test due to the above-mentioned large amount of evidence of its reliability and validity, as well as the well-established normative data across populations. Furthermore, a dexterity test will be designed and built, looking to provide the experimental studies with a customizable, flexible, and cost-effective tool to test and acquire kinematic data from the most frequently used grasping patterns according to Bullock et al. [88].

The use of abstract tasks in this custom-built test will expand on findings by Light et al. on the effects of familiarity and object shape on the performance of manipulative tasks, providing quantifiable data on the differences between daily living tasks and abstract tasks.

2.7 Analysis of Human Movement

Human biomechanics is the inter-discipline that describes, analyses, and assesses human movement. It involves a wide range of movements, from gait to the lifting of a load to athletic performance. All cases are governed by the same physical and biological principles, the difference from case to case being the specific tasks and the level of detail of each movement [97].

Biomechanics is an old branch of life and physical sciences, dating back to renaissance scientists interested in the application of mechanics to biological problems, making use of principles from physics, chemistry, mathematics, physiology, and anatomy.

Human movement science integrates a number of areas of study, such as neurophysiology, exercise physiology, and anatomy. In general terms, it studies movement in different contexts and the factors related to the analysis, improvement and recovery of physical activity.

The process of human movement starts with the sensory system providing information regarding the environment, the state of the body, and parameters related to the end-goal of the movement. The neuromuscular system controls the generation of energy and the activation of fiber muscles to produce movement. The characteristics of the muscle activation is a function of the physiological characteristics of the muscle (i.e., fiber type), the state of the muscle (rested vs. fatigued), and the task. The resultant tension produces moments at each joint center, generating movement at the skeletal level [97], [98]. Finally, two or more joints collaborate toward a common goal, performing a coordinated movement to complete a task [97], [99], [100].

Any quantitative assessment of human movement must be preceded by measurements and descriptions, followed by the biomechanical analysis if more detail is required.

The first assessment level is based on direct observation, and as such is subjective and almost impossible to compare with any observations made previously. Observers must describe the observations, emphasising any changes, conclude based on their knowledge and analysis, and end up with potential causes. When it is possible to acquire any measurements of the patient's movement, then data can be analysed and processed to objectively describe the movement. Finally, at the highest level of assessment, the assessor can explore a range of biomechanical analyses (mathematical operations that are performed on a set of data to present them in another form or to combine the data from several sources to produce a variable that is not directly measurable) to accurately find causes of problems, rehabilitation patterns, or risk factors.

The analysis of human movement and particularly hand movement is one of the underlying requirements for an accurate understanding and evaluation of dexterity and the relationships between hand movement patterns, their causes, and their effects on object interactions. Thus, it is important for this research to understand the different phases of human movement studies.

2.7.1 Kinematic Analysis of the Hand

Kinematics describe the variables that are involved in the movement of points, bodies, and systems of bodies without consideration of the masses of those objects nor the forces that cause that movement [99].

Kinematic variables include linear and angular displacements, velocities, and accelerations. The displacement data is usually acquired from the centre of gravity of body segments, centres of rotation of joints, extremes of limb segments, or other key anatomical landmarks. The spatial coordinate system in which the variables are defined can be either relative or absolute. A proper kinematic analysis requires relative coordinates to be reported relative to an anatomical coordinate system that changes from segment to segment. The absolute system has its coordinates referred to an external coordinate system [97], [101], [102].

The kinematic description of a body segment may produce a number of time-changing variables, such as position (x, y, z), linear velocity, linear acceleration, angle of a segment, angular velocities, and angular accelerations, depending on the required level of analysis [97], [103], [104].

A large volume of data and calculations are needed in order to fully and accurately describe any human movement, and it usually results in reports and graphic plots that are complex and large enough to make them difficult to interpret and assess. Thus, a kinematic analysis may use only a fraction of all the possible kinematic variables [97].

The kinematic analysis of the lower limbs has been consistently looked at in biomechanics research for a variety of clinical applications, allowing for the development of powerful and accurate tools and methods to measure movement parameters and reaction forces. The main interest of lower limb research is focused on gait movements and the development of reliable numerical models, looking to define ranges of motion and pathological patterns [98], [105]–[107].

Compared to gait analysis however, the primary function of the hands is highly variable and adaptive for manipulating tasks, increasing considerably the complexity of the problem. There is no single standard activity for the hands, and the free nature of hands and finger movements allows for little restrictions and repeatability as compared to gait [98].

Several activities of daily living (ADL) have been suggested in the literature as standard functional tasks in clinical studies of the hands and upper limbs [5], [19], [108], [109]. The majority of these studies suggest tasks related to personal care and feeding, involving a significant variability of execution in the normal population. Furthermore, the hand and fingers have a relatively large number of degrees of freedom, with a very large working range, compared to the lower extremity.

Thus, most of the knowledge and methods developed for lower limbs analysis are not easily transferable to the analysis of the hand. Various proposals and techniques have been developed through the years to acquire and analyse kinematic data from the upper extremities, with emphasis on the repeatability and physiological significance of the results [12], [14], [15], [19], [29], [102], [109]–[111].

Traditionally, kinematic variables of each hand joint was measured using goniometers, electrogoniometers and, more recently, instrumented gloves. The main limitation of these methods is the difficulty in measuring ranges of motion from the fingers joints simultaneously, because of the size of the segments involved, and the number of connecting cables interfering with both the acquisition and the performance of the experimental tasks. Moreover, a number of studies have shown how all of these methods can be affected by many sources of errors, caused by the examiner and the instrument [112]–[116].

Compared to the methods based on goniometers and instrumented gloves, a motion capture system will be presumably more time-consuming, due to setting-up time, and more expensive, since it requires an equipped laboratory and maintenance.

Motion capture systems, however, have the advantage that they do not require connecting cables between fingers and system, which can restrict finger movement. Moreover, motion capture does not need customization for different hand sizes, unlike instrumented gloves.

Normally, motion capture methods are based on the measurement of instantaneous positions of markers located on the skin surface using either conventional video (passive markers) or sensors (active markers). The resulting representation used to estimate the kinematic variables consists of a kinematic chain of links, with each link representing a portion of the human body referred to as body segment. The body segments are connected by joints with various degrees of freedom, with the number of segments and joints constraints contributing to the number of degrees of freedom of the general representation [107].

Regardless of the motion capture system used, the output of the acquisition stage is a file of x,y,z coordinates of each of the markers at each sample point in time. These coordinates are defined in a laboratory global reference system. The next phase of the process involves the transformation of the global coordinates data into the anatomical axes of the body segments so that a kinematic analysis can be performed to obtain absolute joint angles, velocities, and accelerations [97].

A few studies have been conducted aiming at simplifying upper extremity and hand motion capture protocols, while at the same time improving their accuracy, repeatability and suitability to a wider range of applications.

Carpinella et al. [117] proposed a quantitative and objective method based on the kinematic analysis of hand segments and on the calculation of global and local parameters, aiming mainly at the evaluation of the hand's voluntary range of motion and maximal opening of the fingers and thumb.

Unlike previous methods [16], [118], [119], this protocol also includes the evaluation of the thumb, providing information about the level of global opening of the hand. However, it does not allow a complete kinematic analysis of the trapezometacarpal and metacarpophalangeal joints of the thumb. Carpinella's protocol was shown to reliable and accurate when considering the analysis of fingers two–five, with precision between 5.5° and 10.4° (mean value: 7.3°), comparable to values obtained with other methods, allowing for the evaluation of all fingers simultaneously with fewer calibration points than previous methods [16], [18], [120].

Zhang et al. [12] described an algorithm for deriving finger segmental centre of rotation (COR) locations during flexion–extension from measured surface marker motions on digits 2 to 5. The algorithm computes an empirically quantifiable relationship between the local movement of a surface marker around a joint and the joint flexion–extension. The protocol proposed by Zhang et al. fits a least-squares plane to the trajectories of four markers on each of the digits. The coordinates of the four markers are then projected onto the flexion-extension plane, allowing for the computing of joint centres to be carried out in two dimensions.

Zhang's work importance relies in that it can lead to an accurate description of fundamental bone kinematics, with results presenting a highly linear relationship between surface marker excursion and the marker-defined flexion–extension angle (the average R^2 in linear regression ranged from 0.89 to 0.97) [12], [121], providing an effective method for the recognition of possible kinematic alteration due to pathological conditions.

Moreover, the motion capture protocol developed and used for this study considerably reduced the number of markers required, with all markers being placed at palpable anatomical landmarks, improving the consistency, while minimizing the demand on the motion capture systems' recognition capabilities.

It should be noted, however, that the complete application of Zhang's algorithm is computationally demanding, requiring for the complex optimization algorithm to be solved for each data set of individual motion trials.

Aiming to further reduce the number of markers required for a hand movement motion capture acquisition, Sancho-Bru et al. [20] developed a protocol that uses a simplified kinematic measuring technique for the hand.

Sancho-Bru's technique consists of the registration of the three-dimensional coordinates of 29 reflective surface markers in two hand static reference postures to allow the calculation of physiological joint rotation angles. The rotation angles at each joint were obtained by superposing the proximal coordinate systems of the reference and tasks postures, and computing the required rotation angles between the distal coordinate systems.

In order to compute the physiological joint rotations from the orientation between consecutive segments, it would be necessary to know the position and orientation of the anatomical rotation axes. In this simplified technique, however, Sancho-Bru considers the kinematic approximation that the flexion/extension axes are perpendicular to the segments, and the flexion/extension and abduction/adduction axes are perpendicular between them.

This protocol allows for the measurement of all degrees of freedom of the hand while at the same time reducing the number of markers makes this protocol suitable for its use in a wider range of applications. Sancho-Bru reported on the errors, accuracy, and repeatability associated with his protocol, with a global error of 6.68° and relatively small errors in repeatability and reproducibility (3.43° and 4.23°, respectively). Furthermore, the method accuracy was calculated by comparing results with data from electronic goniometers, showing no statistically significant difference and high correlation between both techniques.

Since the simplified kinematic measuring technique was found to be a reasonable approximation, the joint rotation axes can be considered as an acceptable estimation of the real physiological joint rotation axes. Moreover, the study renders additional evidence of the potential of simplified markers' topology for an accurate kinematic analysis of hand and finger movement.

A different approach for surface markers placement and acquisition of wrist, fingers, and thumb movements was developed by Metcalf et al. [122], placing 26 reflective markers on palpable anatomical landmarks proximal to the joint on the distal head of the proximal bone. The protocol allows the calculation of flexion/extension and radial/ulnar deviation of the wrist, flexion/extension of the dorsal aspect of the transverse metacarpal arch, finger flexion/extension at the MCP PIP, and DIP joints, finger abduction/adduction at the MCP, flexion/extension of the MCP and IP joints of the thumb, as well as abduction/adduction and rotation through to opposition of the thumb, by calculating the angular movement between two planes or two vectors. The proposed method is time-efficient (marker placement taking between 3-5 min) when compared against previous protocols, and accurate (mean repeatable accuracy of 5.1°). Moreover, the configuration of the markers proved to be repeatable between raters, and differences between repeated measures of a static reference frame were within a degree of each other, demonstrating the protocol can be applied in clinical research studies [122].

These studies have contributed to the development of efficient and accurate acquisition protocols, by adjusting traditional movement measuring techniques to meet the particular requirements of hand and finger movement, reducing the number of markers, designing time-efficient and accurate marker topologies, and developing computational methods to calculate the necessary kinematic variables. By adjusting marker topologies and the computation of kinematic variables, these methods incur in simplifications, not taking into consideration potential sources of errors such as skin movement or correct definition of joint centres. However, the wide range of potential applications and the possibility of acquiring accurate hand and finger movement data during the performance of manipulative tasks may help in the development of our understanding of hand function and hand movement patterns. This research will build on these simplified acquisition techniques to obtain and analyse kinematic data during the performance of both ADLs and dexterity tests. The analysis techniques will build on findings on grasping patterns, interactions with objects, and standardisation of assessment of hand function for clinical research.

2.7.2 Kinematic Synergies

One of the biggest challenges faced in the analysis of hand motion is that natural movements of the hand rarely involve motion or rotation at a single joint. Many studies have shown that a small number of combined joint motions (synergies) can account for most of the variance in observed hand movement patterns and postures [12], [23], [25], [26], [123]. Simultaneous correlated motion at multiple joints has been studied during more sophisticated uses of the hand, such as typing [8], playing the piano [28], or haptic interactions [29]. Even when normal subjects are instructed to move one finger, correlated movement occurs in the adjacent fingers [27].

In most of these studies, principal component analysis (PCA), and cross-correlation of kinematic variables have been used to show the role of kinematic synergies in hand function [12], [22], [29], [124], [125].

Principal component analysis is based on the reduction of the dimensionality of the original data set, while retaining as much as possible the original variation in the data. This reduction is based on transforming the original variables to a newly defined set, named principal components, ordered according to the contribution to variation of all the variables. PCA allows to describe a grasping pattern with a small set of coefficients, with different patterns having different coefficients, therefore facilitating comparisons between patterns and parameters [97], [124], [126].

Studies using PCA have been focused on explaining the correlated rotation of multiple joints during grasping by a much smaller number of principal components, identifying coordinated joint movements as kinematic synergies during hand dexterous movements [24], [26], [123], [124], [127].

Mollazadeh et al. examined the possibility that motor cortex might control the hand through such synergies by collecting simultaneous kinematic and neurophysiological data from monkeys performing a reach-to-grasp task. They used PCA, to extract kinematic synergies from 18 joint angles in the fingers and wrist and analyzed the role of the components in tasks comparing against individual joints data. Although the first principal component proved to account for a large amount of variance during movements, their conclusions did not provide evidence of the role of synergies within the motor cortex system. Nevertheless, their findings suggested that the motor cortex might adapt the synergies generated by subcortical centers, allowing interdependent finger movement and providing the hand with the ability to grasp a wide variety of objects [124].

In an attempt to contribute to the overall understanding of kinematic synergies and their relation with muscle synergies, Tagliabue et al. [24] used PCA to analyse reach-grasp-and-pull kinematics and muscle activity. Tagliabue et al. split the precision grip into three phases: reach, grasp-and-pull, and static hold. Principal component analysis on each phase revealed that kinematic and muscle synergies simultaneously adjust to perform a grasping pattern at different task conditions. Moreover, their results rendered evidence of the presence of synergies during the reaching phase, with the hand forming the precision grip.

The use of PCA to study other grasping patterns and the role of kinematic synergies throughout the three phases of grasp may produce additional information on grasping pattern selection, and the effects of environment and object characteristics during the performance of manipulative tasks.

An alternative approach to studying the variability in human movement involves the use of nonlinear dynamics principles, with techniques such as vector coding and continuous relative phase (CRP) [128]–[130]. Both methods assess coordination by quantifying phase plane trajectories of oscillators with fundamentally different approaches. In vector coding, the phase plane is limited to spatial information from positional data, while in CRP the phase plane contains both position and velocity information[130].

Continuous relative phase (CRP) is often used to measure the coordination between two joints or two segments by characterising them as oscillators, and has been used to analyse stability and variability during manual coordination tasks [131] and gait cycles [129], as well as the effects of coordinative variability in overuse injuries [132].

Vector coding on the other hand has been used to measure the relative motion between the angular time series of two joints or segments in studies to identify abnormal gait patterns and alterations in coordination in sports applications [128], [131], [133]. Vector coding analysis provides a measure of coordination variability using only spatial information (joint angles) and has been shown to be a more useful clinical tool than CRP, mainly because of its proved ability to provide conclusions from original positional data. Both methods, however, provide valid measures of movement variability from a dynamical systems perspective, although both present limitations when applied to cycles that present discontinuities [126], [128], [133].

For the purposes of this research, and aiming to build on our understanding of grasping patterns strategies, synergistic behaviour during manipulative tasks, and the role of finger interdependence in dexterity, PCA will be applied to reduce the relatively large number of variables and interpret results from finger positional data. Due to the task-specific nature of the majority of the above-mentioned studies, the author deems it necessary to further investigate a wider range of grasping patterns accounting for dexterous manipulative tasks, particularly those involved in activities of daily living. Furthermore, analysis of individual tasks' phases will provide information on the effects of object shape, familiarity, and task goal on the performance of grasping movements.

2.7.3 Trajectory analysis

Research into the field of computational motor control has shown that efficient, regular movements are smoothest in either their kinematic or the motor control aspects [134]–[136]. Based on these findings, many studies have evaluated quality of hand movement based on smoothness, normally measured by jerkiness (rate of change of acceleration). However, other measures are possible and have been investigated, including counting peaks in speed [42], [137], normalized mean speed, and mean arrest period ratio [42].

Smoothness has been used as a measure of movement quality for both healthy subjects [32], and people suffering from hand impairment conditions, such as stroke [30], [42], [138], arm ataxia [36], and Parkinson's disease [38]. Moreover, smoothness in the minimum-jerk sense has been shown to account for the two-thirds power law, widely considered an invariant in human movement [41].

The study of smoothness as measure of movement quality has been mostly focused on patients recovering from stroke, with studies concluding that a characteristic feature of the earliest movements made by patients recovering from stroke is their lack of smoothness, mainly due to the presence of a series of discrete sub-movements [34]. Evidence of sub-movements has also been found in the movements of healthy individuals [139]. Although the existence of sub-movements in upper limb movements characterized as healthy has not been demonstrated unequivocally, it has been shown that they account for many patterns in human movement [33], [44].

Flash and Hogan [33] studied the coordination of voluntary human arm movements, developing a mathematical model to predict both the qualitative and quantitative details of planar multi-joint arm movements.

Their experimental observations confirm that unconstrained motions are approximately straight with smooth bell-shaped tangential velocity profiles, while curved motions have portions of low curvature joined by portions of high curvature. Their mathematical model matched observed human planar arm movements and the optimization of the curvature allowed for the description of many different hand trajectories.

Rohrer et al. [42] used a robotic therapy device to analyse five different measures of movement smoothness in the hemiparetic arm of patients recovering from stroke. In their study, Rohrer et al. computed jerk, normalized mean speed, mean arrest period ratio, number of peaks of speed, and the ratio of sub-movements.

The study involved the collection of the smoothness metrics at different stages of the therapy process, comparing the metrics with results from the commonly used Fugl-Meyer Test of Upper Extremity [140]. Four of the five metrics showed general increases in smoothness as the patients underwent therapy, and a computer simulation of recovery based on sub-movement blending suggested that progressive blending of sub-movements underlies stroke recovery.

Findings from the study confirmed that subject's increased movement smoothness with recovery is a result of well developed coordination. Additionally, the fact that many subjects showed an increase in the jerk metric during recovery indicates an important difference between jerk-based measures of smoothness and sub-movement assessment. The behaviour of the jerk metric in the study suggested that, during post-stroke recovery, minimizing jerk may not be the primary criterion accounting for refinements in movement patterns.

Hogan and Sternad [30] further studied the sensitivity of smoothness measures, particularly jerk-based measures, and demonstrated that jerk-based measures with dimensions vary counter-intuitively with movement smoothness, unlike dimensionless jerk-based measures, which directly and accurately quantify common deviations from smooth movement. In conclusion, the study proved that quantities based on the integrated magnitude of derivatives such as jerk are simple to implement and provide an intuitively meaningful measure of shape and smoothness when they are appropriately scaled to be dimensionless.

Osu et al. [138] focused on the quantification of movement by three-dimensional curvature (mathematically described as an inverse of the radius of curvature at the each point on the trajectory) of hand movement, aiming to establish a novel measurement independent of movement duration. In their study, Osu et al. compared the curvature with the Stoke Impairment Assessment Set (SIAS) [141] score and the jerk measure representing temporal smoothness.

Curvature was comparable to examiner's observation, as well as to a clinical assessment of functional recovery as measured by SIAS, suggesting that the quality of paretic movement is best characterized through spatial smoothness represented by curvature. Additionally, the smaller computational cost involved in this measurement suggests that this method may be a viable tool in clinical research settings.

Researchers in the above mentioned studies applied different smoothness measures, each of which scales differently with movement amplitude and duration and intervals of arrest. This is an important consideration when assessing hand function for daily living tasks, since manipulative tasks are normally composed of a range of movement amplitudes and durations. Furthermore, a comprehensive study of the potential of smoothness measures as indicatives of dexterity on daily living tasks has not been made yet.

2.8 Summary

Previous works have demonstrated that dexterity is not only harmonic movements or proficient execution of movements, it is everything that involves finding a motor solution for any situation and in any condition.

A scientific analysis of dexterity should be done in such a way that it precisely fits most of the features involved in its definition.

Therefore, the analysis and assessment of dexterity should provide the tools to detect and quantify the intrinsic nature of the phenomenon. It should be based on measures of the biomechanical parameters of hand movement and it must include an analysis of the relationship between these parameters and real hand function.

A number of studies have considered the kinematic problem in the human body as the process of controlling a complex and redundant system via coordinative structures or functional synergies, and they have been able to successfully identify common patterns in healthy and impaired hands. Although most of these efforts have not included the simultaneous measurement of all degrees of freedom involved in manipulative tasks, making significant simplifications to measure and analyse kinematic variables, progress has been made in making these studies accurate and precise by utilising of a combination of data acquisition techniques and analysis protocols to understand the kinematics problem.

Analysis of the complex capacity of dexterity will also require an analysis of the basis of movement patterns, taking into consideration the role of individual fingers, and the effects of grasping strategies and object characteristics.

In this research an effort was made to develop and test a method to understand and assess dexterity, building on findings from previous studies, and aiming to provide the clinical research and movement science fields with a set of measures to subjectively quantify a number of factors involved in proficient hand movement.

Chapter 3

Development of the Variable Dexterity Test: Construction, reliability and validity

3.1 Introduction

The main aim of this research is the development and testing of a dexterity quantification method that takes into account a robust definition of dexterity and includes factors that account for proficient movement patters. The experimental studies have been planned to build on findings regarding grasping pattern choice, effects of object size and shape on manipulative tasks, analysis of kinematic synergies, and characterization of dexterous finger movement. In order to acquire data from the range of grasping patterns identified from the literature [87], [88], and looking to produce a flexible, cost-effective, and customisable experimental tool, a dexterity test apparatus was designed and built. A second objective was to produce an abstract tasks test that provides information on the effects of task familiarity and grasping pattern choice when compared against tasks related to activities of daily living.

The kinematic analysis of abstract tasks in this custom-built test will look to expand on findings by Light et al. on the effects of familiarity and object shape on the performance of manipulative tasks, as well as conclusions from studies investigating the development of grasping skills [58], [67], [81], providing quantifiable data on the differences between daily living tasks and abstract tasks.

This chapter describes the design and construction of the dexterity test tool. This test will provide the experimental studies of this research with a flexible, cost-effective traditional timed test that covers a larger set of grasping patterns. Moreover, this chapter will include the methods and results from validity and reliability studies for this new test.

3.2 Method

3.2.1 Test Design

Various studies have demonstrated the great range of postures and motions of the hand, and the difficulty of defining a standardized set of tasks and movements that truly reflect the quality of hand function in everyday activities. Most of the available studies agree on a basic classification of grip styles that can be synthesized into four prehensile patterns: precision, cylinder, spherical, and extended, depending on the position of the fingers, the opposition of the thumb, and the areas of contact with the object being held [5], [63], [83], [86]. The

Variable Dexterity Test (VDT) was designed to provide the experimental studies of this research with a tool to assess the most frequently used grip styles during the performance of activities of daily living: cylinder, precision, and spherical [63], [87], [88] (Table 3.1).

TABLE 3.1 FREQUENCY AND DURATION DATA FROM BULLOCK ET AL. STUDY FROM 7.45 HOURS OF TYPICAL DAILY LIVING ACTIVITIES OF HOUSEKEEPERS AND MACHINISTS

Grasp	Duration proportion (%)	Frequency (%)	
Cylinder	23 ± 2	14 ± 0.5	
Precision	26 ± 1	37 ± 0.4	
Spherical	21 ± 1	15 ± 2	

The Variable Dexterity Test is made of four subtests each aimed at assessing hand movement and proficiency of manipulation during abstract tasks that require the performance of the selected grip styles.

The first three subtests are performed on a 270mm x 420mm and 15mm deep square wooden board with 8 holes. Each of the holes measures 10mm in depth and 74mm in diameter. Holes are separated from each other by 40mm in 2 rows of 4 holes each (Figure 3.1-A). A second wooden board is used for the extended spherical subtest. The dimensions of the board are 440mm x 365mm, and 10mm deep. The board has 6 holes. Each of the holes measures 10mm in depth and 113mm in diameter (Figure 3.1-B). Holes are separated from each other by 44mm in 2 rows of 3, fitting larger 112mm objects that require the use of the extended spherical grasping pattern.

The spherical subtest is made of 8 circular abstract objects (74mm diameter) with no handle. Participants are asked to grab the objects with a spherical grip, extending digits 1-5 and pressing the pulps of the fingers against the perimeter of the object (Figure 3.2-A). The extended spherical subtest consists of 6-114mm diameter circular objects with participants required to hold the objects using a spherical grip style (Figure 3.2-B). The assessment of spherical grips of different sizes was planned in order to objectively quantify the effect of object size in manipulative strategies and movement patterns across tasks. Additionally, the spherical grip has been shown to have a wider range of variability related to the degree of finger extension and adduction [142], [143].

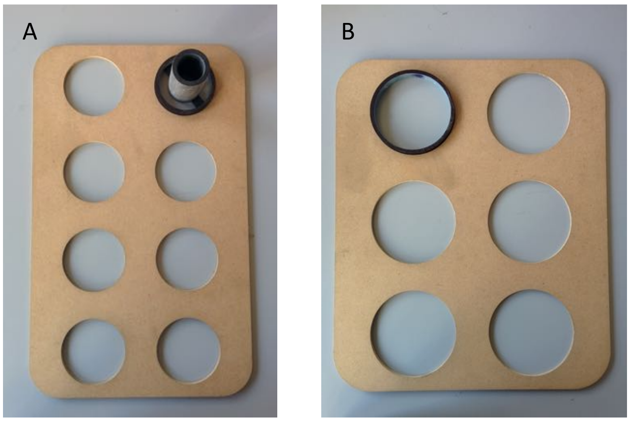


FIGURE 3.1 THE TWO WOODEN BOARDS OF THE VDT. A) BOARD USED FOR THE PRECISION, CYLINDER AND SPHERICAL SUBTESTS. B) BOARD USED FOR THE EXTENDED SPHERICAL SUBTEST

The precision subtest consists of 8 handles (30mm high and 70mm) that can be attached to the basic circular plastic shapes of the spherical subtest. Participants are asked to pick and manipulate the objects using the handle with a precision grip style, holding the object on the radial aspect of the distal interphalangeal joint of the middle finger, the pulp of the index finger, and the pulp and distal interphalangeal joint of the thumb (Figure 3.2-C).

The cylinder subtest is made of 8 attachable cylinders (80mm in height, 40mm diameter). The cylindrical handles are attached to the original circular objects and participants are asked to use the handles to manipulate the objects, performing a cylinder grip, also known as power grip. During the cylinder grip the fingers and the thumb flex and close around the object, applying pressure with both proximal and distal phalanges and using the palm to stabilise the control over the object (Figure 3.2-D).

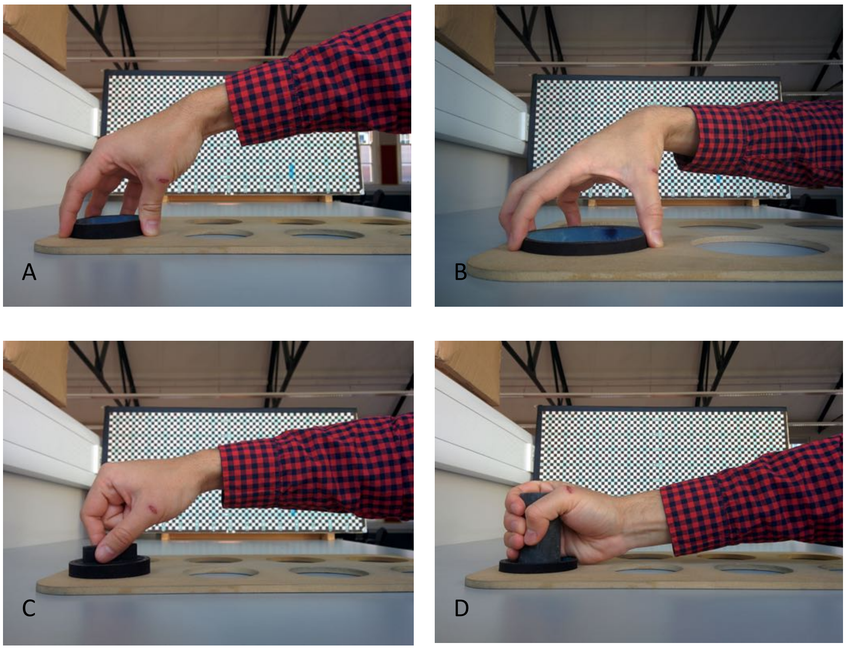


FIGURE 3.2 THE FOUR SUBTESTS OF THE VDT. A) SPHERICAL, B) EXTENDED SPHERICAL, C) PRECISION, D) CYLINDER

3.2.2 VDT Standard Procedure

The test board corresponding to the required subtest is placed 10 cm from the edge of a table where the participant is comfortably sitting on a standard chair. The objects are placed arranged in two symmetric rows aligned 10 cm to the side of the board corresponding to the participant's dominant hand.

The participant is instructed to pick up one object at a time with the dominant hand, using the corresponding grip style, starting with the object at the top (away from participant) and place it in a hole of the board starting at the top-opposite side of the board. The participant will continue until she or he has put all the objects onto the board.

The following verbal instructions should be provided to the participant: “Please start with your dominant hand. Start by picking up the object at the top far row and place it in the hole at top opposite side of the board, pick and place all the objects as quickly as possible, finishing with the object at the bottom proximate row. If you drop an object, time is stopped, and a 5-second penalty is added. Continue to pick and place the objects with the object that you just dropped. The clock starts where it was stopped, and the time is continued.”

The examiner demonstrates each subtest by doing 2 objects. The participant is asked to practice by doing the test one time. Each subtest is then performed once, and the examiner records the time it takes to complete every subtest, along with the penalties and unusual movement patterns observed.

The score is the time it takes the participant to put all the objects on the board. For every time a participant drops an object, time is stopped, and a 5-second penalty is added. Both penalized and non-penalised times are registered. The definition of the 5-second penalty was based on the grosser nature of the tasks, and the time it may take to re-locate the object for a second trial. Additionally, the use of penalised scores was thought to provide clear, noticeable abnormalities in the data for further analysis.

The examiner should note any unusual movement during completion of the test as well as a description of the main grasping pattern features for each subtest. The final score, time plus penalties is the level of dexterity for each specific grip style.

Time, penalties, final score and notes regarding movement patterns should all be included in the assessment of the participant's dexterity performance for each of the types of dexterity under analysis.

3.2.3 Reliability Study

The extent to which a measurement is consistent is called reliability. Reliability estimates were obtained from a pilot group of 24 healthy participants (11 female, 13 male, mixed backgrounds: 8 Asian, 12 European, 4 Latin American). A power analysis was conducted for a repeated measures ANOVA to define the sample size for 80 per cent power at the 5 per cent level of significance (Figure 3.3, Table 3.2).

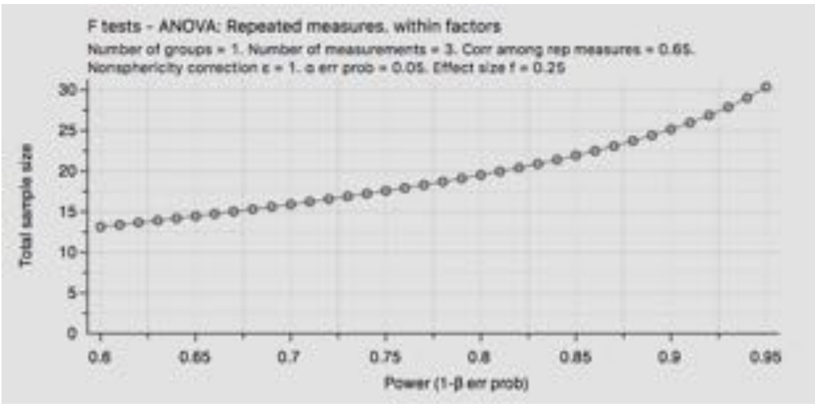


FIGURE 3.3 POWER CURVE SHOWING HOW THE SAMPLE SIZE AFFECTS THE POWER OF THE TEST

TABLE 3.2 POWER ANALYSIS PARAMETERS

Effect size	p value	Power	Number of groups	Sample size
0.25	0.05	0.88	1	24

The purpose of the study was to demonstrate that each subtest is truly objective. In order to be considered objective, the test must produce consistent results among the pilot group with both a single assessor (test-retest reliability) and multiple assessors (inter-rater reliability).

A first rater assessed one control group (24 healthy participants, 13 males ranging in age from 20 to 50 years and 11 females ranging in age from 22 to 45 years), with 3 replicate evaluations for each subject (Table 3.7). To establish test-retest reliability, it is necessary to show there is no statistically significant effect in the replicate trials. The most appropriate method to determine whether the data have test-retest reliability is by an analysis of variance (ANOVA) with the null hypothesis being that no significant difference exists between replicates. The null hypothesis was tested at a p level of 0.05.

Inter-rater reliability was assessed for the same pilot group with 3 raters administrating the VDT. The F value obtained from the ANOVA must exceed a critical value (3.13), which is based on the 95% confidence interval in order to prove that the null hypothesis should be rejected and, therefore, that there is a statistically significant difference between replicates. The analysis of variance was performed for all subjects and replicates on a subtest-by-subtest basis under the assumption that if all subtests are repeatable, then the complete assessment can be considered as reliable.

3.2.4 Validity Study

In order to know if the test is measuring what it is intended to measure, the relationship between scores on the VDT and performance of related activities of daily living was examined.

The VDT was administered to the control group, and the scores were correlated with the participant's ability to perform 4 activities of daily living—opening a soft drink bottle, tying shoelaces, opening a jar, and buttoning a shirt- as representative of activities that require the use of the VDT's grip styles (Figure 3.4).

The selection of activities of daily living was made based on results from previous studies found in the literature review [5], [61], [88], [108].

FIGURE 3.4 PARTICIPANTS PERFORMING ACTIVITIES OF DAILY LIVING SELECTED AS REPRESENTATIVES OF THE SPHERICAL, PRECISION, AND CYLINDER GRIP STYLES: A) OPENING A JAR, B) OPENING A PLASTIC BOTTLE, C) BUTTONING A SHIRT.

An examiner recorded the time of completion of each of the ADLs and Bi-serial Correlation was performed to determine whether a relationship exists between each of the 4 subtests of the VDT and the selected tasks.

Validity was also tested by correlating scores of the new test with scores of an established test, known as the gold standard. The relationships between scores from the VDT and the Purdue Pegboard Test [3] were evaluated for the same control group. The Purdue Pegboard Test was chosen as the standard because of its proved reliability and validity, as well as its long history of usage and reliability among a wide range of disciplines and applications [3], [9], [47], [91], [92].

3.3 Results

3.3.1 Reliability

Analysis of variance indicated no significant differences between replicates on participants who received instructions from one instructor (test-retest) (Table 3.7). The analysis of variance was performed for all subjects and replicates on a subtest-by-subtest basis under the assumption that if a procedure is repeatable, then the complete assessment can be considered as reliable. The F critical value was not exceeded for any of the 4 subtests (Table 3.3).

TABLE 3.3 TEST-RETEST ANOVA RESULTS FOR ALL OF THE VDT SUBTESTS

	Sum of Squares	df	Mean Square	F	Sig.
VDT-Spherical					
Between Groups	7.441	2	3.721	2.136	.126
Within Groups	120.172	69	1.742		
Total	127.613	71			
VDT-Extended spherical					
Between Groups	7.370	2	3.685	1.027	.363
Within Groups	247.520	69	3.587		
Total	254.890	71			
VDT-Precision					
Between Groups	10.242	2	5.121	1.750	.181
Within Groups	201.878	69	2.926		
Total	212.120	71			
VDT-Cylinder					
Between Groups	10.901	2	5.451	2.089	.132
Within Groups	180.017	69	2.609		
Total	190.918	71			

The ANOVA test revealed an F maximum value of 2.136 (F critical value 3.13) and *P* minimum value of 0.126 for the VDT-Spherical subtest, while the VDT-Cylinder had an F value of 2.089, indicating that, although well within the reliability region, these subtests are less repeatable than the others. Means and standard deviations from the scores of each sub-test further confirm this pattern, with VDT-Cylinder and Spherical resulting in larger standard deviations across subjects (Table 3.7). Repeatability was considerably improved after the first trial, with second and third trials having smaller differences across subjects.

The inter-rater ANOVA test showed statistically significant effect for one subtest. The VDT-Spherical was shown to have significant differences between raters (F = 3.601, F critical value = 3.13, P = 0.033) at the 95% confidence interval level. For the other three subtests the examiner appears to have statistically little effect on the performance of the test, with a maximum F value of 1.653 and minimum P value of 0.199 for the VDT-Cylinder subtest, thereby indicating inter-rater reliability (Table 3.4).

TABLE 3.4 INTER-RATER ANOVA RESULTS FOR ALL OF THE VDT SUBTESTS

	Sum of Squares	df	Mean Square	F	Sig.
VDT-Spherical					
Between Groups	7.614	2	3.807	3.601	.033
Within Groups	72.938	69	1.057		
Total	80.552	71			
VDT-Extended spherical					
Between Groups	8.146	2	4.073	1.347	.267
Within Groups	208.597	69	3.023		
Total	216.743	71			
VDT-Precision					
Between Groups	6.683	2	3.342	1.007	.370
Within Groups	228.874	69	3.317		
Total	235.557	71			
VDT-Cylinder					
Between Groups	8.938	2	4.469	1.653	.199
Within Groups	186.525	69	2.703		
Total	195.463	71			

3.3.2 Validity

Correlation between precision activities and the scores on the VDT-Precision subtest was 0.644 for buttoning and 0.603 for shoelaces, indicating there is correlation between performance of this subtest and activities requiring finer dexterity (Significance at the 0.01 level, 2-tailed).

The VDT-Cylinder and VDT-Spherical, subtests showed correlation with activities requiring grosser dexterity (power, cylinder and spherical grip styles), with the highest correlation being those found between VDT-Cylinder and Opening a soft drink bottle (0.707) and between VDT-Spherical and Opening a soft drink bottle (0.646) (Table 3.5).

TABLE 3.5 PEARSON CORRELATION BETWEEN VDT SUBTESTS AND RELATED ACTIVITIES OF DAILY LIVING

	VDT Precision/ Tying Shoelaces	VDT Precision/ Buttoning a shirt	VDT Cylinder/ Opening soft drink bottle	VDT Spherical/ Opening soft drink bottle
Pearson Correlation	0.603	0.644	0.707	0.646
Significance (2-tailed)	0.002	0.001	0.0001	0.001
N	24	24	24	24

The Pearson Bi-serial correlation between the scores on the Purdue Pegboard Test Right Hand and those subtests of the VDT that require finer dexterity was high (-0.813 for the VDT-Spherical, -0.849 for the VDT-Precision, and -0.617 for the VDT Cylinder subtest) indicating the VDT selected subtests results agree with those coming from a well established dexterity test (Table 3.6).

TABLE 3.6 PEARSON CORRELATION BETWEEN VDT SUBTESTS AND PURDUE PEGBOARD TEST

	VDT Precision/PPBT	VDT Spherical/ PPBT	VDT Cylinder/PPBT
Pearson Correlation	0.849	0.813	0.617
Significance (2-tailed)	0.0001	0.001	0.001

TABLE 3.7 SCORES, MEANS, AND STANDARD DEVIATIONS FROM THE 4 SUB-TESTS OF THE VDT

Subject	VDT Precision	VDT Cylinder	VDT Spherical	VDT Extended Spherical
	14.82	15.18	13.64	10.72
1	13.77	15.02	13.08	9.67
	14.09	14.89	13.22	9.55
Mean	**14.23**	**15.03**	**13.31**	**9.98**
SD	**0.54**	**0.15**	**0.29**	**0.64**
	13.45	16.23	13.12	12.31
2	13.55	15.66	13.23	11.90
	12.92	15.53	12.55	11.21
Mean	**13.31**	**15.81**	**12.97**	**11.81**
SD	**0.34**	**0.37**	**0.37**	**0.56**
	15.41	15.18	14.43	11.23
3	14.98	15.02	14.20	11.10
	15.07	14.45	13.97	10.78
Mean	**15.15**	**14.88**	**14.20**	**11.04**
SD	**0.23**	**0.38**	**0.23**	**0.23**
	13.76	16.38	14.57	10.96
4	12.88	14.90	14.15	10.50
	13.01	14.86	13.65	10.11
Mean	**13.22**	**15.38**	**14.12**	**10.52**
SD	**0.48**	**0.87**	**0.46**	**0.43**
	15.08	15.88	13.89	12.56
5	13.14	13.89	12.75	12.32
	13.85	13.66	12.89	11.87
Mean	**14.02**	**14.48**	**13.18**	**12.25**
SD	**0.98**	**1.22**	**0.62**	**0.35**
	15.67	21.30	15.77	16.77
6	15.06	19.32	15.19	16.14
	14.48	19.29	14.80	15.83
Mean	**15.07**	**19.97**	**15.25**	**16.25**
SD	**0.60**	**1.15**	**0.49**	**0.48**
	16.93	17.87	14.90	14.24
7	16.64	19.30	16.12	14.58
	16.36	17.26	15.97	15.04
Mean	**16.64**	**18.14**	**15.66**	**14.62**
SD	**0.29**	**1.05**	**0.67**	**0.40**
	16.27	16.07	13.68	11.24
8	15.12	15.45	13.13	11.05
	15.34	14.90	13.25	10.78
Mean	**15.58**	**15.47**	**13.35**	**11.02**
SD	**0.61**	**0.59**	**0.29**	**0.23**
	13.73	13.16	12.21	9.29
9	12.90	12.57	12.78	9.67
	12.61	13.40	11.69	10.33
Mean	**13.08**	**13.04**	**12.23**	**9.76**
SD	**0.58**	**0.43**	**0.55**	**0.53**
	12.34	14.63	12.68	11.73
10	11.18	14.32	10.98	10.18
	11.56	13.44	11.38	11.11
Mean	**11.69**	**14.13**	**11.68**	**11.01**
SD	**0.59**	**0.62**	**0.89**	**0.78**
	11.98	14.21	12.01	10.36
11	11.74	13.82	10.90	9.58
	11.13	13.78	10.98	9.73
Mean	**11.62**	**13.94**	**11.30**	**9.89**
SD	**0.44**	**0.24**	**0.62**	**0.41**
	16.47	15.56	14.79	13.51
12	16.03	15.10	14.11	13.44
	15.50	14.76	13.96	13.87
Mean	**16.00**	**15.14**	**14.29**	**13.61**
SD	**0.49**	**0.40**	**0.44**	**0.23**
	15.34	16.54	13.69	12.56
13	14.12	15.13	12.13	12.70
	14.44	15.35	12.45	11.66
Mean	**14.63**	**15.67**	**12.76**	**12.31**
SD	**0.63**	**0.76**	**0.82**	**0.56**
	11.66	14.20	11.97	12.61
14	11.52	12.31	9.40	9.80
	11.55	13.17	9.68	9.36
Mean	**11.58**	**13.23**	**10.35**	**10.59**
SD	**0.07**	**0.95**	**1.41**	**1.76**

15	12.65 12.01 12.12	13.20 12.20 12.77	12.34 11.76 11.10	10.01 9.66 9.11
Mean	**12.26**	**12.72**	**11.73**	**9.59**
SD	**0.34**	**0.50**	**0.62**	**0.45**
16	16.60 15.13 14.65	15.12 14.87 14.45	14.57 14.01 13.91	14.02 13.21 12.68
Mean	**15.46**	**14.81**	**14.16**	**13.30**
SD	**1.02**	**0.34**	**0.36**	**0.67**
17	11.88 10.99 11.14	14.41 14.05 13.92	12.02 12.10 11.22	12.81 11.53 12.12
Mean	**11.34**	**14.13**	**11.78**	**12.15**
SD	**0.48**	**0.25**	**0.49**	**0.64**
18	16.29 15.87 15.02	17.11 15.08 15.45	14.10 13.78 13.13	12.99 11.25 11.11
Mean	**15.73**	**15.88**	**13.67**	**11.78**
SD	**0.65**	**1.08**	**0.49**	**1.05**
19	15.88 14.12 14.80	15.40 15.01 13.65	13.78 12.69 13.80	13.91 13.03 12.90
Mean	**14.93**	**14.69**	**13.42**	**13.28**
SD	**0.89**	**0.92**	**0.64**	**0.55**
20	11.77 11.18 11.10	14.88 14.01 14.36	13.11 12.67 12.05	14.18 13.87 13.56
Mean	**11.35**	**14.42**	**12.61**	**13.87**
SD	**0.37**	**0.44**	**0.53**	**0.31**
21	14.78 14.03 13.66	15.45 15.12 14.86	12.81 12.10 11.93	12.18 12.01 11.45
Mean	**14.16**	**15.14**	**12.28**	**11.88**
SD	**0.57**	**0.30**	**0.47**	**0.38**
22	12.13 11.33 11.89	15.55 15.11 14.67	13.79 13.65 12.90	15.25 14.76 14.21
Mean	**11.78**	**15.11**	**13.45**	**14.74**
SD	**0.41**	**0.44**	**0.48**	**0.52**
23	13.67 13.14 13.55	14.55 14.15 13.74	12.77 12.04 12.18	10.50 10.33 9.89
Mean	**13.45**	**14.15**	**12.33**	**10.24**
SD	**0.28**	**0.41**	**0.39**	**0.31**
24	16.17 15.71 15.13	17.13 16.58 16.92	14.45 13.98 14.51	14.97 14.14 15.02
Mean	**15.67**	**16.88**	**14.31**	**14.71**
SD	**0.52**	**0.28**	**0.29**	**0.49**

3.4 Discussion

The VDT was designed to supply the experimental studies with a flexible, effective tool to assess a range of grasping patterns. The VDT proved to be time-efficient (time for administration about 30 seconds to 2 minutes) and provides information regarding the patient's ability to perform precision, cylinder, and spherical grasping patterns. Reliability and validity studies indicate good inter-rater and test-retest reliability of the measure. Analysis of variance showed that the VDT is repeatable between replicates 2 and 3 on participants who received instructions from one instructor (the F critical value was not exceeded for any of the 4 subtests). Although scores' differences between first and second trials (Tale 3.7) across participants may suggest a learning effect. Differences between second and third trials were considerable smaller, suggesting a diminished learning effect once participants were familiar with the task. This results and are in line with those obtained from previously developed abstract tests [1], [4], where participants are required to perform a practice trial to reduce the effects of unfamiliarity.

The Spherical subtest was shown to be the less repeatable among the VDT subtests according to the results from the ANOVA, although still well-within repeatability region. This result may be due to the generally shorter times to complete this subtest when compared to the others (Table 3.7). The size of the object may also affect performance, with participants performing the spherical and cylinder tasks considerably faster than the precision task.

Inter-rater reliability from the VDT-Spherical proved to be significantly lower ($F = 3.601$, F critical value = 3.13, $P = 0.033$) than that from the other three subtests, further stressing the need to explore changes due to object size in hand manipulative tasks.

The VDT subtests scores were correlated with the measured times to complete a selection of activities of daily living. The VDT-Precision subtest showed a strong correlation with a selection of activities of daily living that require a precision grip. The highest correlation was found between the VDT-Cylinder and the opening of a soft drink bottle (0.707), indicating that the performance of that activity is highly influenced by the proficient execution of a cylinder grip style.

Moreover, results from the Pearson correlation between tasks and the VDT show a general trend relating proficiency to perform daily living tasks with scores in the VDT.

Similarly, Pearson Bi-serial correlation showed that there is a strong relation between the VDT-Precision subtest and the Purdue Pegboard test (-0.849 for the VDT-Precision), indicating that the proposed method delivered results that are consistent with those delivered by a well established, reliable dexterity test. As expected, the Spherical and Cylinder subtests (0.617 for the VDT-Cylinder) showed lower correlation coefficients with the Purdue Pegboard Test, since they are not designed to assess the same movement pattern.

There are a number of limitations in the design and performance of the VDT. The timed nature of the score provides limited information on overall functionality, measuring only speed of performance, which is not hand function. Furthermore, the examiner's ability to measure time accurately and reliably has been shown to be limited by previous works on the subject [1], [5], [9], with Light et al. proposing the use of a self-timed technique to avoid this variability [5]. Additionally, results from the validity study may have been influenced by familiarity, with the pegboard test involving a new skill, whereas the selection of ADLs involved the use of well-known objects and interactions.

This study revealed the standard assessment procedure needs further development, with clearer details regarding initial posture, configuration of the board and parts, and instructions on the use of particular grasping patterns.

Future studies may include a prospective normative study involving a larger number of participants across healthy and impaired populations, and over a wide age span. Moreover, effects of object shape and size, and variability due to examiner's error must be investigated. Further standardisation of the assessment protocol could improve reliability and consistency, and the efficiency of test administration may be improved by not stopping the clock when a participant drops an object.

The experimental studies of this research will make use of the VDT to provide data from abstract tasks across the range of grasping patterns, along with activities of daily living and the Purdue Pegboard Test, looking to gain insight into the factors accounting for proficient hand movement and further analyse the role of object shape, size, and familiarity during the grasping action.

Chapter 4

Kinematic Analysis of Hand Function

4.1 Introduction

Computerised three-dimensional kinematic analysis is being increasingly used in clinical practice as a standard tool for the evaluation of interventions in patients with motor or postural dysfunction, especially in the case of gait and spinal posture [106], [107], [120], [144].

In the case of the hand, different techniques have been used in the past to analyse motor function, such as goniometers, instrumented gloves or motion tracking from digital images [50], [113], [116]. Many of these techniques do not allow for the simultaneous measurement of all degrees of freedom and may interfere with the normal development of the hand activities. In this sense, the motion tracking of passive markers from video images (motion capture) is a good choice, as although some movement restriction can be introduced by using passive markers, it is much lower than using instrumented gloves or electronic goniometers [16], [120], [145]–[148].

Errors induced by skin movement have been shown to be larger than motion capture errors, with the pattern and magnitude of the errors dependent on tasks, body segments, and subjects. However, there are still discrepancies between the values reported by different authors due to the range of measuring techniques used, and the large variability of marker topologies [107], [111], [120], [149].

Traditionally, optical motion capture methods are based on the measurement of instantaneous positions of markers located on the skin surface and they can be either based on passive markers or active markers. The resulting representation is then used to estimate a set of variables from a kinematic chain of links, with each link representing a portion of the human body referred to as body segment. The body segments are connected by joints with various degrees of freedom, with the number of segments and joints constraints contributing to the number of degrees of freedom of the general representation [107].

The output from a motion capture system is a file of *x*,*y*,*z* coordinates of each of the markers at each sample point in time. These coordinates are defined in a laboratory global reference system. These global coordinates are then transformed into the anatomical axes of the body segments so that a kinematic analysis can be performed to obtain absolute joint angles, velocities, and accelerations [97].

The primary function of the hands is highly variable and adaptive for manipulating tasks, increasing considerably the complexity of the measuring technique. There is no single standard activity for the arms and hands, and the free nature of finger movements allows for little restrictions and repeatability as compared to gait [98]. Furthermore, manipulative tasks are often performed in reduced volumes, with fingers and objects interacting rapidly, and markers easily interfering with normal movement.

Thus, most of the knowledge and methods developed for lower limbs analysis are not easily transferable to the analysis of the hands. Various proposals and techniques have been developed to acquire and analyse kinematic data from the hands, with emphasis on the repeatability and physiological significance of the results, while at the same time adapting to the particular challenges presented by the measurement of finger movement [12], [14], [15], [19], [29], [102], [109]–[111].

In order to obtain physiological joint rotations from the orientation between consecutive segments, it would be necessary to know the position and orientation of the anatomical rotation axes. Simplified techniques, however, have allowed the measurement of all degrees of freedom of the hand while at the same time reducing the number of markers, making this protocols suitable for a wider range of applications [15], [20], [21], [122]. By adjusting marker topologies and the computation of kinematic variables, these methods incur in simplifications, not taking into consideration potential sources of errors such as skin movement or correct definition of joint centres. Detailed descriptions of these studies and their reported accuracy was summarised in the literature review chapter of this dissertation.

This experimental study aims to develop and pilot a hand movement measuring technique based on simplified marker topologies found in the literature, emphasising viability, and reducing potential sources of disturbances to natural hand movements.

The simplified nature of the designed measuring technique conveys the above-mentioned limitations, however, the protocol and analysis techniques may provide the clinical research field with a number of metrics and analytical procedures looking to build on previous efforts to standardise assessment of hand movement.

In this study, motion capture data from healthy participants performing dexterity tests and activities of daily living was used to produce two sets of variables: instantaneous joint angles variables, and trajectory variables. The resulting data was then used to identify movement patterns related to quality of movement and dexterous tasks, focusing on the most frequently used grip styles identified from the literature.

The kinematic data acquisition protocol and methodology are described in the first part of this chapter, along with the characteristics of the motion capture system. The second part of the chapter details the processing of the motion capture data to compute joint angles and trajectory variables, as well as the post-processing, analysis, results, and discussion from these experimental studies.

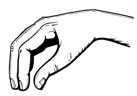
4.2 Acquisition of Kinematic Data

4.2.1 Experimental Protocol

This pilot study examined 9 healthy participants (5 male, 4 female, all right-handed, age 22-38 years, 26 ± 6.2 years) performing the Purdue Pegboard Test, the Variable Dexterity Test, and a selection of tasks related to activities of daily living: opening a soft drink bottle, picking up a coin, drinking from a glass, opening a jar and buttoning a shirt. The sample size is underpowered to fully test the reliability and validity of the protocol but will be sufficient to consider feasibility issues and will offer trend level data to indicate the preliminary value of this approach to hand movement measurement (effect size 0.5, power 0.51).

The activities of daily living were selected as representative of tasks requiring the performance of the three most frequently used grip styles according to the literature: precision (pinch), cylinder (power), and spherical grip styles (Table 4.1). The selection of dexterity tests includes the Purdue Pegboard Test as a well-established, reliable hand function test, and the Variable Dexterity Test, a flexible, cost-efficient test that assesses the selected prehensile patterns and was designed and developed as part of this research.

TABLE 4.1 SELECTION OF ACTIVITIES OF DAILY LIVING AND THEIR ASSOCIATED GRIP STYLE

Task	Associated Grip Style	
Opening a bottle	Precision	
Picking up a coin	Precision	
Drinking from a glass	Cylinder	
Opening a jar	Spherical	

Buttoning a shirt	Precision	

All movements began in a consistent seated posture with the torso upright, the right upper arm approximately vertical and forearm horizontal, the fingers in natural full extension (abduction/adduction not specified), and the palm resting on a specified area on the table.

The standardized experimental protocol was developed by testing range of motion, motion capture protocols and subjects' positions and participants were evaluated by a single tester, trained to use both standardized procedures and motion capture systems.

Test-retest consistency of the protocol was assessed through a paired *t*-test with alpha level at 0.05 and with hypothesis testing based on confidence intervals of the test-retest data. The differences did not vary in any systematic way over the range of measurement and all measurements were within the 95% limits of agreement.

The participants carried out a total of three repetitions of each experiment: a first practice trial to familiarise with the tasks, followed by two trials, with a 10-second pause between each trial.

In the first experiment, participants performed the three sub-tests of the Variable Dexterity Test (VDT). All three sub-tests require the participant to reach forward over a distance of approximately 25 cm to grasp one object at a time and place it into a hole on a board as rapidly as possible with the right hand. The VDT-Precision sub-test requires the manipulation of a solid object with a rectangular-shaped handle by using the precision grasping pattern. The VDT-Cylinder sub-test requires the use of the cylinder/power grip pattern to grasp and manipulate a cylinder-shaped handle. The VDT-Spherical sub-test makes use of a plastic circular object and requires the participant to use a spherical grip style.

In the fourth task, subjects performed the Purdue Pegboard Test, reaching forward over a distance of approximately 35 cm to grasp a metal peg (2 mm in diameter), placing it into a hole on the Purdue Pegboard, and returning the hand to the initial posture.

In experiment 5 the participants performed the selection of tasks related to activities of daily living: opening a jar (spherical grip style), picking up a one-pound coin, opening a plastic bottle, and buttoning a shirt (precision grip style), and drinking from a glass (cylinder grip style). The subjects maintained the same initial posture as in the first experiment and reached forward over a distance of approximately 25 cm to grasp the object (400ml jar, one pound coin, 250ml glass respectively, 300ml bottle of water, men's shirt), performed the instructed task, and returned the hand to the initial posture after releasing the object.

4.2.2 Motion Capture Setup

The acquisition technique consisted of the placement of 25 reflective markers (24-4mm markers 4mm, and 1-8mm) on different anatomical hand landmarks.

From the index to little fingers, five markers were placed as follows: first marker on the metacarpal base, second marker on the knuckle, third on the proximal interphalangeal (PIP) joint, fourth on the distal interphalangeal (DIP) joint and, finally, the fifth marker on the nail.

For the thumb, the first marker was placed on the metacarpal base, a second marker on the MCP joint, the fourth on the IP joint and the fifth marker on the nail. One marker was placed on the wrist, aligned with the middle finger, on the wrist dorsum (Figure 4.1).

FIGURE 4.1 MARKER SET USED FOR THE DATA ACQUISITION

A ten-camera Vicon T-160 opto-electronic motion capture system (Oxford Metrics Ltd., UK) recorded the reflective marker movements at a sampling frequency of 120 Hz, and then output the time-varying marker coordinates in a three-dimensional laboratory coordinate system (X–Y–Z) established through calibration. The laboratory setup was designed to fit the working volume of manipulative tasks, with the cameras focusing on the table. The table's surface was covered with black matte paper to avoid errors due to reflection (Figure 4.2).

FIGURE 4.2 MOTION CAPTURE LABORATORY SETUP

The calibration process consists of the definition of the capture volume's origin and the use of a calibration wand to allow the system to determine room geometry in the volume where the motion will be occurring (Figure 4.3). Once all the cameras are calibrated and the image error in marker recognition has been reduced to acceptable levels (less than 0.15) the system is ready for the acquisition.

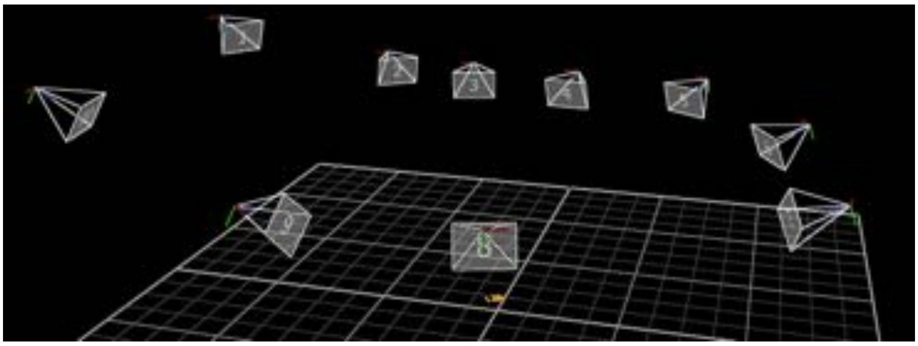


FIGURE 4.3 CAPTURE VOLUME AND POSITION OF THE CAMERAS RELATIVE TO THE PARTICIPANTS' HAND

A local coordinate system X_0–Y_0–Z_0 was established to facilitate kinematic descriptions and definitions (Figure 4.4). The origin of this local coordinate system was the marker adhered to the dorsal landmark of wrist. The coordinates of the markers measured in the global (laboratory) coordinate system (X –Y –Z) were transformed and expressed in the local coordinate system (X_0–Y_0–Z_0).

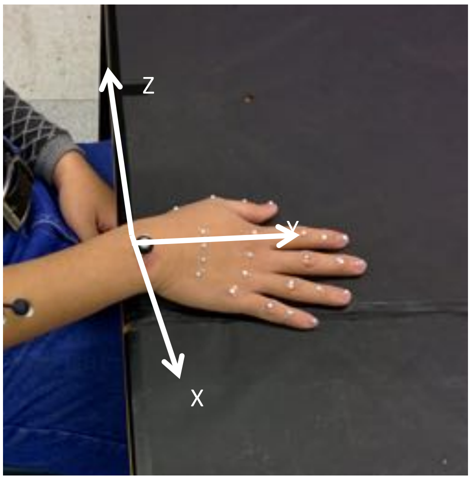


FIGURE 4.4 LOCAL COORDINATE SYSTEM

4.2.3 Processing of Motion Capture Data

The local coordinate system on the dorsum of the right hand was defined using measured global coordinates of four markers: W, I1, M1, and L1 (Figure 4.5). The origin is the marker placed at the Wrist landmark (W). The X-Y plane coincides with the plane formed by Wrist, I1, and L1 markers. The Y-axis is the projection of W–M1 vector onto the plane, pointing distally. The X-axis is perpendicular to the X-axis, pointing to the ulnar. The Z-axis is normal to the X Y plane, pointing dorsally.

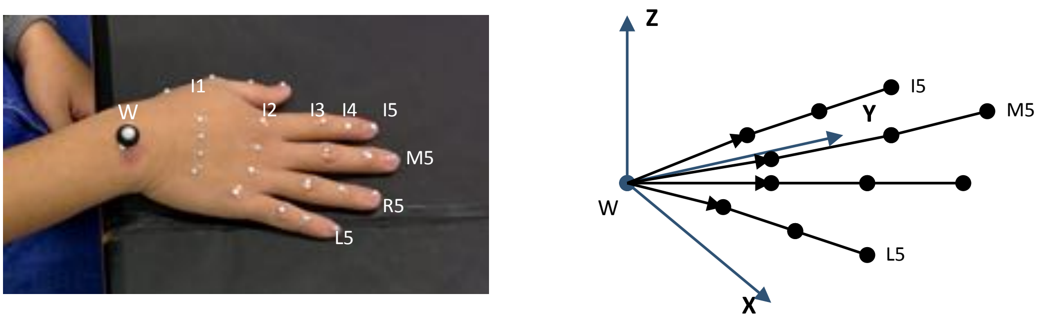


FIGURE 4.5 MARKER SET AND DEFINITION OF THE LOCAL REFERENCE SYSTEM

In order to transform the laboratory reference system to the local coordinate system, the axis system x,y,z needs to be rotated into the system denoted by x''',y''',z''' (Figure 4.6). Following a Cardan sequence (x-y-z), rotation about the x axis occurs first, about the new y axis second, and about the new z axis last. The first rotation is θ_1 about the x axis to get x',y',z'. Because we have rotated about the x axis first, x will not be changed and $x' = x$, while the y axis changes to $y'$and the z axis to z'. The second rotation is θ_2 about the new y'

axis to get x'',y'',z''. Because this rotation has been about the y' axis, $y'' = y'$. The final rotation is θ_3 about the new z'' axis to get the desired x''', y''', z'''.

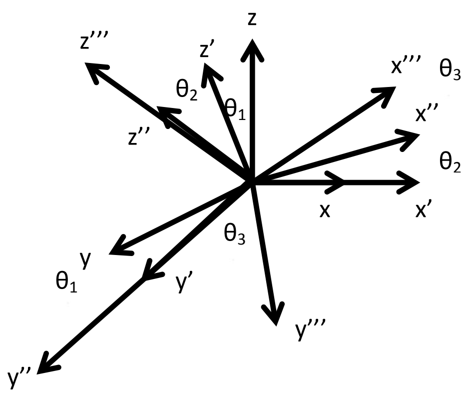


FIGURE 4.6 CARDAN SEQUENCE OF THREE ROTATIONS ABOUT THE X,Y,Z AXES. THE FIRST ROTATION IS ABOUT THE X AXIS TO GET X', Y', Z'; THE SECOND ROTATION IS ABOUT THE NEW Y' AXIS TO GET X'', Y'', Z''; AND THE FINAL ROTATION IS ABOUT THE NEW Z'' AXIS TO GET THE DESIRED X''', Y''', Z'''.

Assuming that we have a point with coordinates x_0 , y_0 , z_0 in the original x , y , z axis system, that same point will have coordinates x_1, y_1, z_1 in the x', y', z' axis system. Based on the rotation θ_1:

$$x_1 = x_0$$

$$y_1 = y_0 \cos\theta_1 + z_0 \sin\theta_1$$

$$z_1 = -y_0 \sin\theta_1 + z_0 \cos\theta_1$$

Using the shorthand notation $c_1 = \cos\theta_1$ and $s_1 = \sin\theta_1$, in matrix notation this may now be written as:

$$\begin{bmatrix} \boldsymbol{x_1} \\ \boldsymbol{y_1} \\ \boldsymbol{z_1} \end{bmatrix} = \begin{bmatrix} \mathbf{1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{c_1} & \boldsymbol{s_1} \\ \mathbf{0} & -\boldsymbol{s_1} & \boldsymbol{c_1} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_0} \\ \boldsymbol{y_0} \\ \boldsymbol{z_0} \end{bmatrix} = [\boldsymbol{\Phi_1}] \begin{bmatrix} \boldsymbol{x_0} \\ \boldsymbol{y_0} \\ \boldsymbol{z_0} \end{bmatrix} \tag{1}$$

After the second rotation θ2 about y', this point will have coordinates x_2, y_2, z_2 in the x'', y'', z'' axis system.

$$\begin{bmatrix} \boldsymbol{x_2} \\ \boldsymbol{y_2} \\ \boldsymbol{z_2} \end{bmatrix} = \begin{bmatrix} \boldsymbol{c_2} & \mathbf{0} & -\boldsymbol{s_2} \\ \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \boldsymbol{s_2} & \mathbf{0} & \boldsymbol{c_2} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_1} \\ \boldsymbol{y_1} \\ \boldsymbol{z_1} \end{bmatrix} = [\boldsymbol{\Phi_2}] \begin{bmatrix} \boldsymbol{x_1} \\ \boldsymbol{y_1} \\ \boldsymbol{z_1} \end{bmatrix} \tag{2}$$

Finally, the third rotation θ_3 about z'' yields the coordinates x_3, y_3, z_3 in the x''', y''', z''' axis system.

$$\begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} = \begin{bmatrix} c_3 & s_3 & 0 \\ -s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = [\Phi_3] \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} \tag{3}$$

Combining Equations (1), (2), and (3):

$$\begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} = [\Phi_3][\Phi_2][\Phi_1] \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} \tag{4}$$

The matrix multiplication shown in Equation (4) is not commutative, thus, the order of the transformations must be such that $[\Phi_1]$ is done first, $[\Phi_2]$ second, and $[\Phi_3]$ last ($[\Phi_1][\Phi_2] \neq [\Phi_2][\Phi_1]$). Equation (4) can be expanded into:

$$\begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} = \begin{bmatrix} c_2c_3 & s_3c_1 + s_1s_2c_3 & s_1s_3 - c_1s_2c_3 \\ -c_2s_3 & c_1c_3 - s_1s_2s_3 & s_1c_3 + c_1s_2s_3 \\ s_2 & -s_1c_2 & c_1c_2 \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} \tag{5}$$

These sets of instantaneous local marker coordinates were subsequently trimmed so that they only contained the portions of hand movement and finger flexion and extension.

To decompose the relative orientation between consecutive defined segments into rotations with physiological meaning, it would be necessary to know the exact position and orientation of the anatomical rotation axes. However, although previous efforts have resulted in a range of techniques and protocols to estimate finger rotation axes with various degrees of success [18], [119], [121], [150], simplified methods have delivered accurate, repeatable, and valid kinematic data with a reduced number of markers and invasiveness [15], [20]. The fundamental kinematic approximation used for this study is that the flexion/extension axes are perpendicular to the segments, and the flexion/extension and abduction/adduction axes in joints with two degrees of freedom are perpendicular between them. Recently, Sancho-Bru et al. [20] studied the errors associated with this kinematic simplification and found a global error of 6.68°, with errors in repeatability and reproducibility lower than 4.5°. Additionally, their study found no statistically significant difference when comparing the simplified approach with the use of electronic goniometers.

The instantaneous flexion angles for digits 2-5 were then obtained by calculating the angle between the pre-defined vectors from the local reference system (Appendix C). The metacarpophalangeal (MCP) flexion angle was defined as the angle between the metacarpal vector and the proximal phalanx vector (Figure 4.7):

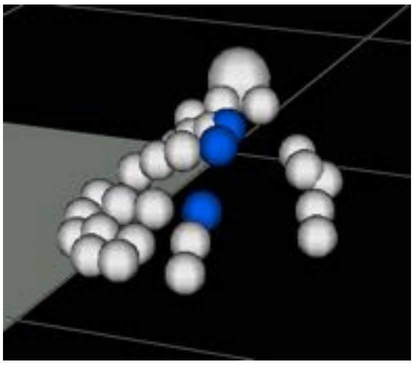


FIGURE 4.7 MARKERS USED TO COMPUTE METACARPOPHALANGEAL FLEXION

$$\overline{\imath MC} = i_1 - i_2$$

$$\overline{\imath PP} = i_2 - i_3$$

$$\theta_{MCPi} = \cos^{-1}\left[\frac{\overline{\imath MC} \cdot \overline{\imath PP}}{|\overline{\imath MC}| \times |\overline{\imath PP}|}\right]$$

The proximal interphalangeal (PIP) flexion was calculated as the angle between the proximal phalanx vector and the middle phalangeal vector (Figure 4.8):

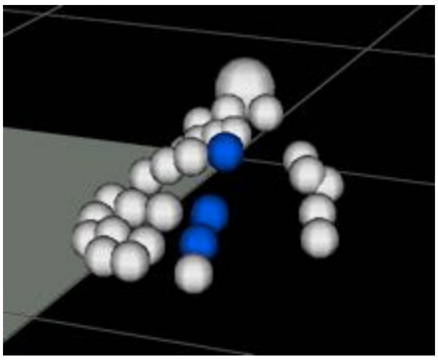


FIGURE 4.8 MARKERS USED TO COMPUTE PROXIMAL INTER-PHALANGEAL FLEXION

$$\overline{\imath MP} = i_3 - i_4$$

$$\theta_{PIPi} = \cos^{-1}\left[\frac{\overline{\imath PP} \cdot \overline{\imath MP}}{|\overline{\imath PP}| \times |\overline{\imath MP}|}\right]$$

The distal interphalangeal (DIP) flexion was defined as the angle between the middle phalangeal vector and the distal phalangeal vector (Figure 4.9):

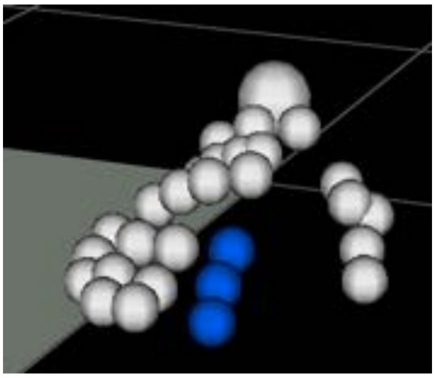


FIGURE 4.9 MARKERS USED TO COMPUTE DISTAL INTER-PHALANGEAL FLEXION

$$\overline{\iota DP} = i_4 - i_5$$

$$\theta_{DIPi} = \cos^{-1}\left[\frac{\overline{\iota MP} \cdot \overline{\iota DP}}{|\overline{\iota MP}| \times |\overline{\iota DP}|}\right]$$

Thumb abduction/adduction was defined as the angle between the thumb's proximal phalanx vector and the vector joining markers T2 and I2 (Figure 4.10):

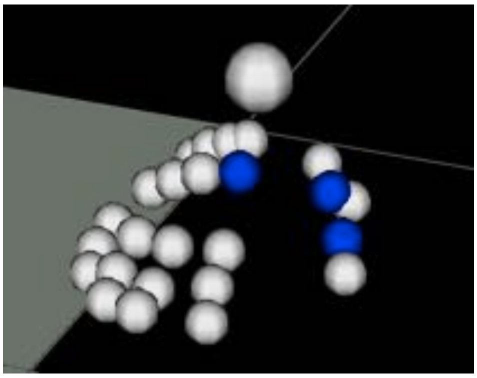


FIGURE 4.10 MARKERS USED FOR THE DEFINITION OF THUMB ABDUCTION/ADDUCTION

$$\overline{tPP} = t_2 - t_4$$

$$\overline{tTI} = i_2 - t_2$$

$$\theta_{tabd} = \cos^{-1}\left[\frac{\overline{tTI} \cdot \overline{tPP}}{|\overline{tTI}| \times |\overline{\iota PP}|}\right]$$

where i represents digits 2-5; i = 2,3,4,5.

4.3 Correlation Analysis of Finger Movement Patterns

4.3.1 Introduction

The analysis of hand movement presents one significant challenge when computing and assessing kinematic variables: the natural movements of the hand rarely involve motion or rotation at a single joint. Previous studies have shown that a small number of joint motions can account for most of the variance in hand movement patterns and postures (kinematic synergies) [12], [23], [25], [26], [123].

Anatomical factors, such as inter-digit webbings, connections between various tendons, insertions of extrinsic finger muscles, and neuronal connections result in mechanical and neural couplings between various joints. The sum of mechanical and neural coupling generates coordinated movements between various joints [22], [25], [123]. Thus, the proficient grasping of an object entails simultaneous motion at multiple joints, with correlated rotations. Correlated motion at multiple hand joints has been studied during complex tasks, such as typing [8], playing the piano [28], and haptic interactions [29], but a standard procedure to assess such movement synergies has not been developed. Moreover, previous studies involved sets of tasks and hand postures or force patterns that were not specific enough to be immediately translated into assessment practice [22], [25], [40].

The purpose of this experimental study was to objectively identify and examine finger movement patterns as one of the underlying features of dexterity and their relation with performance of daily living tasks.

Finger landmark positions obtained from motion capture, within and across digits 2–5 (index to little finger) were processed to obtain instantaneous joint angles from healthy participants performing the Purdue Pegboard Test, Variable Dexterity Test, and a selection of tasks related to activities of daily living. The study focused on the three main grip styles identified from the literature as the most frequently used grasping patterns: precision, cylinder, and spherical.

4.3.2 Data Analysis

The analysis of joint angles correlations consisted of the computation of the cross-correlation coefficient matrix for all instantaneous flexion joint angles of interest obtained from motion capture data. A matrix X, whose rows are observations (instantaneous joint angles) and whose columns are variables (degree of freedom), was defined from data from the last trial of each task for each subject in order to reduce error due to learning effect and provide stability to the data.

The matrix R of correlation coefficients was calculated from the matrix X. The matrix R is related to the covariance matrix C by:

$$\boldsymbol{R(i,j)} = \frac{\boldsymbol{C(i,j)}}{\sqrt{(\boldsymbol{C(i,i)C(j,j)})}} \tag{6}$$

Where R, is the zeroth lag of the normalized covariance function.

Significance of the correlation values was examined for $p < 0.5$, and for all correlation coefficients $n = 10$, $df = 15$.

The matrix R was calculated for three stages of each trial, splitting tasks into**:** formation of the grip, manipulation, and release; this approach increases the precision of the analysis. providing insight into the range of strategies across grasping patterns.

The stages were defined by visual inspection of data and video. The formation stage was defined as the portion of the task between the start of the movement and the first contact with the object. The manipulation stage was defined as the period of the task between the first contact of the dominant hand with the object and the moment no contact between the hand and the object is detected. Finally, the release stage was defined as the portion of the task starting when the hand stops making contact with the object and ending with the hand back in the resting posture (Figure 4.11).

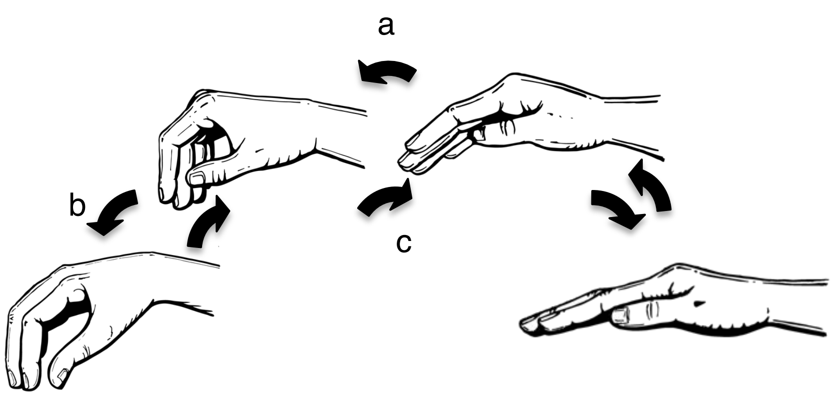


FIGURE 4.11 PREDEFINED TASKS' STAGES: A) FORMATION OF THE GRIP, B) MANIPULATION, C) RELEASE (TAKEN FROM EXPERIMENTAL FOOTAGE)

The correlation coefficients across tasks and participants were then analysed aiming to identify the relationship between finger movement patterns and dexterity. Additionally, correlation patterns from both dexterity tests were compared to the related ADL looking to investigate the degree with which these tests truly reflect finger movement patterns and hand function.

4.3.3 Results

Purdue Pegboard Test

Formation stage: In the Purdue Pegboard Test experiment the metacarpophalangeal (MCP) joints of the index and middle fingers showed high correlation coefficients between them (0.8 - 0.95) during the formation stage of the task (Table 4.11). The MCP of the thumb, however, had low correlation coefficients with respect to the MCP of index and middle fingers. Correlation coefficients between all the joints analysed fell during the final segment of the formation stage, when the hand approached the object and prepared to make contact with the board, this was particularly noticeable in the correlation coefficients between the MCP joint of the thumb and the same joint of the index and middle fingers (Figure 4.12, Table 4.2).

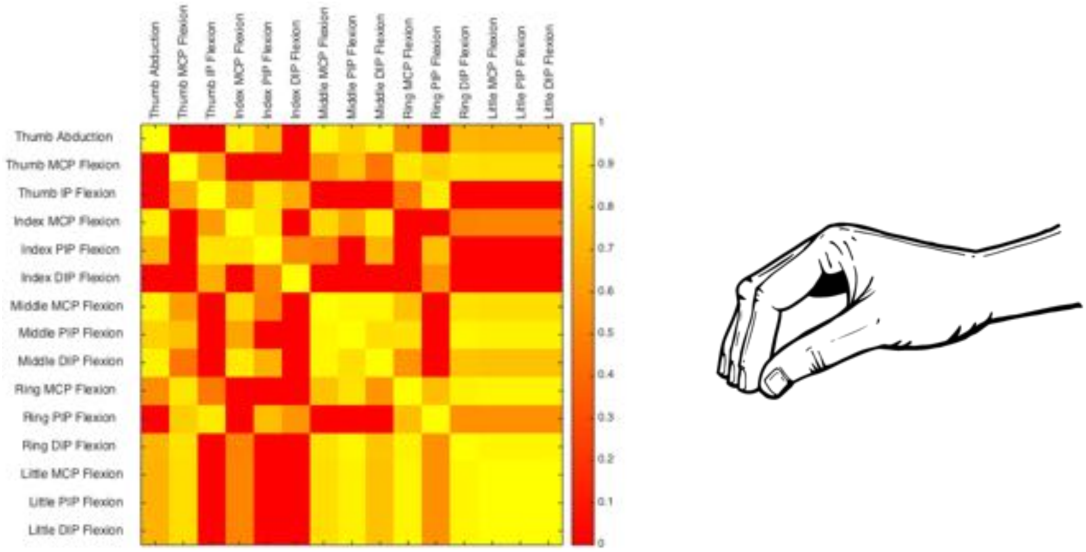


FIGURE 4.12 COLOUR MAP SHOWING THE CORRELATION COEFFICIENTS BETWEEN ALL MEASURED MOVEMENTS FROM SUBJECT 4 DURING THE FORMATION STAGE OF THE PURDUE PEGBOARD TEST. RED COLOUR INDICATES LOW CORRELATION. SIGNIFICANCE OF THE CORRELATION COEFFICIENTS WAS EXAMINED FOR P < 0.5. THE IMAGE ON THE RIGHT SHOWS THE POSTURE OF THE HAND ACCORDING TO THE CROSS-CORRELATION MAP, WITH INDEX FINGER AND THUMB MOVING INDEPENDENTLY FROM THE REST OF THE FINGERS (RED AND ORANGE COLOURED AREAS CORRESPONDING TO FLEXION MOVEMENTS OF THESE DIGITS).

Manipulation stage: During the manipulation stage, the MCP joint of the thumb had low correlation values with respect to the MCP joints of both the index and middle fingers (0.2 - 0.5) (Table 4.11). The MCP joints of index and middle fingers showed higher correlation values between them during the first part of the manipulation stage. The last part of the manipulation stage, which includes the insertion of the peg into the hole, produced low correlation values for all the joints under analysis (0.3 - 0.5) (Table 4.2, Appendix D).

Release stage: During the release stage of the test correlation values between the MCP joints of index and middle fingers raised to levels above 0.8 for most subjects, while correlation coefficients from movements involving the thumb increased when compared with previous stages, showing a smooth and coordinated extension of this fingers during the dissolution of the grasping pattern (Table 4.2, 4.11, Appendix D).

TABLE 4.2 MEANS AND S.D. VALUES OF THE CORRELATION COEFFICIENTS FROM MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE PURDUE PEGBOARD TEST

	Formation stage		
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb
Subject	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.81 (0.08)	0.25 (0.03)	0.18 (0.12)
2	0.73 (0.1)	0.44 (0.048)	0.29 (0.086)
3	0.86 (0.094)	0.33 (0.09)	0.2 (0.11)
4	0.83 (0.053)	0.41 (0.087)	0.39 (0.079)
5	0.92 (0.032)	0.3 (0.098)	0.19 (0.10)
6	0.82 (0.072)	0.26 (0.074)	0.41 (0.099)
7	0.8 (0.075)	0.36 (0.091)	0.333 (0.12)
8	0.85 (0.044)	0.38 (0.11)	0.38 (0.15)
9	0.81 (0.079)	0.42 (0.092)	0.46 (0.079)
	Manipulation stage		
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb
	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.69 (0.059)	0.41 (0.12)	0.54 (0.083)
2	0.51 (0.038)	0.33 (0.045)	0.42 (0.094)
3	0.61 (0.082)	0.28 (0.079)	0.49 (0.091)
4	0.65 (0.049)	0.47 (0.086)	0.31 (0.078)
5	0.54 (0.12)	0.32 (0.092)	0.44 (0.12)
6	0.47 (0.095)	0.42 (0.11)	0.21 (0.056)
7	0.57 (0.083)	0.32 (0.067)	0.44 (0.053)
8	0.42 (0.091)	0.23 (0.098)	0.29 (0.68)
9	0.63 (0.11)	0.3 (0.13)	0.57 (0.099)
	Release stage		
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb
	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.81 (0.088)	0.57 (0.035)	0.62 (0.11)
2	0.87 (0.056)	0.49 (0.057)	0.53 (0.079)
3	0.94 (0.034)	0.69 (0.085)	0.59 (0.082)
4	0.82 (0.066)	0.33 (0.12)	0.46 (0.059)
5	0.92 (0.052)	0.21 (0.10)	0.33 (0.048)
6	0.79 (0.089)	0.72 (0.069)	0.65 (0.099)
7	0.91 (0.036)	0.37 (0.087)	0.32 (0.14)
8	0.85 (0.059)	0.32 (0.067)	0.27 (0.095)
9	0.89 (0.075)	0.55 (0.11)	0.59 (0.083)

Variable Dexterity Test - Precision

Formation stage: Data obtained from the performance of the VDT-Precision revealed high correlation between the MCP flexion of index and middle fingers during the formation stage of the task, as the fingers flexed to perform a precision grip. Correlation between the thumb and both index and middle fingers was generally lower across participants, with values below 0.8 for 90% of the subjects (Table 4.3, 4.11).

Manipulation stage: Correlation coefficients during the manipulation stage of the VDT-Precision task were from moderate to high between the index finger's MCP and middle finger's MCP flexion with respect to the rest of the joints. Thumb flexion had moderate correlation with respect to the rest of the movements under analysis for all participants (Table 4.3), indicating the manipulation of the VDT object required higher thumb flexion interdependence with the index and middle fingers across subjects (Table 4.11).

Release stage: The release stage resulted in correlation coefficients below 0.8 for all participants and movements. Index and middle fingers MCP flexion had the highest correlation coefficients across participants, although these values were rarely above 0.75, indicating low finger interdependence across all degrees of freedom, as the fingers extended, and the hand returned to the starting position (Table 4.3, 4.11, Appendix D).

TABLE 4.3 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE VARIABLE DEXTERITY TEST-PRECISION TASK.

		Formation stage	
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
Subject	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.78 (0.098)	0.76 (0.089)	0.54 (0.078)
2	0.58 (0.087)	0.33 (0.056)	0.65 (0.092)
3	0.96 (0.022)	0.73 (0.084)	0.80 (0.084)
4	0.98 (0.024)	0.73 (0.089)	0.72 (0.095)
5	0.92 (0.031)	0.65 (0.059)	0.67 (0.084)
6	0.82 (0.026)	0.71 (0.098)	0.66 (0.093)
7	0.8 (0.044)	0.59 (0.074)	0.58 (0.087)
8	0.85 (0.033)	0.64 (0.082)	0.58 (0.092)
9	0.81 (0.12)	0.42 (0.12)	0.46 (0.081)
		Manipulation stage	
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
	Mean Correlation Coefficient (+/-S.D.)	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.88 (0.045)	0.60 (0.098)	0.59 (0.087)
2	0.50 (0.076)	0.76 (0.089)	0.60 (0.081)
3	0.65 (0.079)	0.65 (0.091)	0.67 (0.079)
4	0.70 (0.11)	0.46 (0.074)	0.43 (0.091)
5	0.78 (0.099)	0.41 (0.093)	0.54 (0.094)
6	0.67 (0.085)	0.61 (0.084)	0.58 (0.074)
7	0.77 (0.092)	0.62 (0.087)	0.56 (0.10)
8	0.69 (0.054)	0.6 (0.12)	0.65 (0.098)
9	0.81 (0.079)	0.54 (0.092)	0.58 (0.092
		Release stage	
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
	Mean Correlation Coefficient (+/-S.D.)	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.60 (0.079)	0.54 (0.091)	0.78 (0.081)
2	0.75 (0.098)	0.27 (0.094)	0.51 (0.078)
3	0.56 (0.11)	0.72 (0.053)	0.58 (0.093)
4	0.68 (0.094)	0.59 (0.067)	0.51 (0.083)
5	0.73 (0.087)	0.71 (0.061)	0.27 (0.090)
6	0.79(0.068)	0.55 (0.082)	0.49 (0.11)
7	0.66 (0.092)	0.58 (0.077)	0.5 (0.079)
8	0.72 (0.088)	0.62 (0.092)	0.55 (0.088)
9	0.69 (0.091)	0.55 (0.071)	0.59 (0.10)

Pick-up Coin task

Formation stage: During the coin experiment, the (MCP) joints of the thumb, index and middle fingers had high correlation values between them in the formation stage (0.8 - 0.95). The MCP joint of the thumb showed lower correlation values with respect to index and middle MCP joints (0.2 - 0.4) for 90% of the subjects (Table 4.4, 4.11).

Manipulation stage: The manipulation stage of the coin task showed high correlation values between the MCP joints of the thumb, index and middle fingers (0.8 - 0.95), indicating a smooth and coordinated grasp and controlled manipulation of the coin across all subjects (Table 4.4, 4.11).

Release stage: In the release stage of the task, the MCP joint of the thumb had the lowest correlation coefficients with respect to the index and middle fingers' MCP joint, fluctuating between 0.2 and 0.8. Additionally, the correlation coefficients between index and middle fingers decreased with respect to previous stages of the task, indicating the dissolution of the grasping pattern presented low coordination between the fingers involved, particularly between the thumb and the index and middle fingers (Table 4.4, 4.11, Appendix D).

TABLE 4.4 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE COIN TASK.

	Formation stage		
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb
Subject	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.82 (0.043)	0.69 (0.049)	0.76 (0.060)
2	0.88 (0.067)	0.61 (0.091)	0.69 (0.081)
3	0.91 (0.033)	0.74 (0.082)	0.82 (0.059)
4	0.87 (0.062)	0.79 (0.052)	0.63 (0.078)
5	0.82 (0.039)	0.62 (0.085)	0.66 (0.049)
6	0.85 (0.051)	0.66 (0.075)	0.77 (0.055)
7	0.93 (0.049)	0.72 (0.086)	0.73 (0.083)
8	0.9 (0.052)	0.84 (0.047)	0.62 (0.078)
9	0.87 (0.071)	0.79 (0.082)	0.71 (0.09)
	Manipulation stage		
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb
	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.81 (0.073)	0.84 (0.09)	0.88 (0.036)
2	0.87 (0.066)	0.89 (0.049)	0.84 (0.047)
3	0.92 (0.042)	0.88 (0.051)	0.89 (0.029)
4	0.90 (0.052)	0.92 (0.025)	0.86 (0.021)
5	0.85 (0.055)	0.82 (0.037)	0.84 (0.051)
6	0.81 (0.068)	0.86 (0.030)	0.91 (0.019)
7	0.91 (0.039)	0.87 (0.053)	0.88 (0.050)
8	0.88 (0.045)	0.9 (0.021)	0.89 (0.043)
9	0.92 (0.029)	0.91 (0.033)	0.91 (0.026)
	Release stage		
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb
	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.78 (0.069)	0.41 (0.083)	0.23 (0.081)
2	0.81 (0.089)	0.52 (0.079)	0.48 (0.085)
3	0.87 (0.042)	0.27 (0.091)	0.35 (0.093)
4	0.83 (0.059)	0.65 (0.084)	0.44 (0.051)
5	0.77 (0.084)	0.72 (0.065)	0.56 (0.065)
6	0.82 (0.062)	0.42 (0.091)	0.39 (0.062)
7	0.80 (0.058)	0.33 (0.087)	0.42 (0.081)
8	0.79 (0.090)	0.39 (0.072)	0.48 (0.075)
9	0.68 (0.081)	0.44 (0.061)	0.64 (0.079)

Buttoning task

Formation stage: In the buttoning experiment, the MCP joints of the index and middle fingers had moderate to high correlation coefficients between them throughout the formation stage of the task (0.75 - 0.90) for 90% of the participants, suggesting a coordinated movement between these MCP joints as the fingers flexed to perform a precision grip (Table 4.5). Correlation coefficients between thumb flexion and both index and middle fingers flexion were lower during this stage, with values below 0.75 for most participants (Table 4.11).

Manipulation stage: During the manipulation stage of the buttoning task, correlation coefficients decreased when compared to the formation stage, particularly index and middle fingers MCP flexion, with coefficients at or below 0.76 for 90% of participants (Table 4.5, 4.11).

Movement correlation between the thumb and index, and middle fingers decreased to levels below 0.65 for all participants. This trend may suggest the finer nature of the task required the fingers to move in an independent manner in order to proficiently complete the task.

Release stage: The release stage was characterised by high correlation coefficients between the index and middle fingers' MCP flexion. 80% of participants had correlation coefficients above 0.80 for the release stage (Table 4.5). Correlation between index and middle finger's flexion with thumb flexion was significantly lower, with 90% of the subjects having coefficients below 60% during this stage of the task. This results may indicate index and middle finger tend to move interdependently when releasing the object, and extending to return to a relaxed posture, while the thumb tends to move in a more independent pattern, normally being the last finger to return to the resting posture (Table 4.11).

TABLE 4.5 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE BUTTONING TASK

	Formation stage		
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
Subject	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.78 (0.055)	0.77 (0.081)	0.71 (0.055)
2	0.87 (0.041)	0.68 (0.058)	0.82 (0.063)
3	0.70 (0.059)	0.65 (0.074)	0.83 (0.079)
4	0.83 (0.062)	0.88 (0.041)	0.59 (0.042)
5	0.85 (0.059)	0.68 (0.090)	0.54 (0.061)
6	0.79 (0.044)	0.64 (0.071)	0.60 (0.079)
7	0.80 (0.082)	0.65 (0.083)	0.58 (0.073)
8	0.76 (0.061)	0.73 (0.069)	0.55 (0.092)
9	0.71 (0.073)	0.66 (0.080)	0.64 (0.071)
	Manipulation stage		
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
	Mean Correlation Coefficient (+/-S.D.)	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.82 (0.048)	0.55 (0.081)	0.62 (0.071)
2	0.71 (0.044)	0.54 (0.067)	0.55 (0.091)
3	0.73 (0.067)	0.64 (0.059)	0.58 (0.062)
4	0.65 (0.051)	0.50 (0.093)	0.58 (0.085)
5	0.76 (0.084)	0.67 (0.088)	0.55 (0.089)
6	0.68 (0.074)	0.52 (0.080)	0.61 (0.052)
7	0.62 (0.059)	0.64 (0.049)	0.59 (0.048)
8	0.72 (0.080)	0.51 (0.091)	0.48 (0.083)
9	0.59 (0.068)	0.55 (0.075)	0.60 (0.086)
	Release stage		
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
	Mean Correlation Coefficient (+/-S.D.)	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.91 (0.033)	0.33 (0.083)	0.33 (0.088)
2	0.86 (0.059)	0.48 (0.075)	0.57 (0.091)
3	0.57 (0.072)	0.62 (0.081)	0.29 (0.052)
4	0.82 (0.045)	0.58 (0.092)	0.55 (0.082)
5	0.88 (0.057)	0.44 (0.063)	0.28 (0.066)
6	0.81 (0.066)	0.52 (0.076)	0.38 (0.073)
7	0.86 (0.049)	0.51 (0.11)	0.44 (0.085)
8	0.87 (0.041)	0.38 (0.072)	0.41 (0.092)
9	0.82 (0.071)	0.58 (0.085)	0.52 (0.087)

Bottle opening task

Formation stage: In the bottle experiment, the index, middle, and thumb MCP flexion were highly correlated throughout the formation stage of the task (0.8 - 0.95) (Table 4.6), suggesting a coordinated finger flexion as the hand prepared the hand posture to manipulate the lid. A variety of precision grips were observed from participants as they reached forward to hold the bottle.

Manipulation stage: Throughout the manipulation stage, the MCP joints of both index and middle fingers had high correlation values (0.8 - 0.95). Correlation coefficients from movements associated with the MCP joint of the thumb, however, presented moderate to low correlation values with respect to the index and middle fingers (0.5 - 0.7) for most subjects (Table 4.6, 4.11). These results may suggest opening the bottle required coordinated movement from index and middle fingers, while the thumb tended to flex and extend in a more independent manner.

Release Stage: The release stage resulted in low correlation coefficients between the MCP joints of the thumb and the index and middle fingers', indicating the dissolution of the grip style was completed with a low degree of interdependencies between the fingers involved in the activity, this behaviour could be generally observed from 80% of the subjects (Table 4.6, 4.11, Appendix D).

TABLE 4.6 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM THE MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE BOTTLE OPENING TASK.

	Formation stage		
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
Subject	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.81 (0.044)	0.93 (0.025)	0.89 (0.043)
2	0.87 (0.051)	0.82 (0.051)	0.84 (0.039)
3	0.92 (0.024)	0.88 (0.040)	0.92 (0.021)
4	0.81 (0.031)	0.8 (0.058)	0.78 (0.041)
5	0.92 (0.026)	0.86 (0.032)	0.83 (0.058)
6	0.88 (0.052)	0.89 (0.026)	0.85 (0.049)
7	0.93 (0.019)	0.91 (0.033)	0.90 (0.025)
8	0.84 (0.069)	0.83 (0.062)	0.88 (0.030)
9	0.88 (0.042)	0.8 (0.069)	0.82 (0.057)
	Manipulation stage		
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
	Mean Correlation Coefficient (+/-S.D.)	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.82 (0.072)	0.57 (0.036)	0.65 (0.044)
2	0.87 (0.051)	0.62 (0.078)	0.72 (0.057)
3	0.93 (0.032)	0.72 (0.081)	0.79 (0.063)
4	0.87 (0.039)	0.61 (0.072)	0.59 (0.055)
5	0.81 (0.052)	0.69 (0.077)	0.66 (0.071)
6	0.91 (0.024)	0.71 (0.089)	0.73 (0.042)
7	0.90 (0.041)	0.77 (0.058)	0.83 (0.051)
8	0.83 (0.072)	0.68 (0.091)	0.74 (0.060)
9	0.89 (0.040)	0.58 (0.087)	0.76 (0.082)
	Release stage		
	MCP Flexion Index MCP Flexion Middle	**MCP Flexion Index MCP Flexion Thumb**	**MCP Flexion Middle MCP Flexion Thumb**
	Mean Correlation Coefficient (+/-S.D.)	**Mean Correlation Coefficient (+/-S.D.)**	**Mean Correlation Coefficient (+/-S.D.)**
1	0.50 (0.062)	0.82 (0.059)	0.81 (0.074)
2	0.29 (0.081)	0.3 (0.066)	0.31 (0.088)
3	0.36 (0.074)	0.33 (0.082)	0.38 (0.073)
4	0.33 (0.084)	0.36 (0.090)	0.35 (0.091)
5	0.55 (0.090)	0.77 (0.083)	0.82 (0.052)
6	0.28 (0.088)	0.31 (0.057)	0.34 (0.081)
7	0.39 (0.092)	0.31 (0.068)	0.40 (0.063)
8	0.41 (0.079)	0.38 (0.074)	0.39 (0.077)
9	0.35 (0.089)	0.32 (0.071)	0.38 (0.090)

Variable Dexterity Test – Cylinder

Formation stage: The highest correlation coefficients during the formation stage of the VDT-Cylinder were observed between middle and ring fingers' MCP flexion, with values varying between 0.60 and 0.94. Coefficients between movements from digits 2-5 were generally larger than those between movements involving the thumb. However, most correlation coefficients were from low to moderate, indicating the formation of the cylinder grip involved mostly independent finger movements before making contact with the object (Table 4.7).

Manipulation stage: During the manipulation stage, the VDT-Cylinder task had moderate to high correlation coefficients for most movements under analysis. Particularly, flexion movements involving digits 2-4 had high correlation coefficients during this stage. Flexion movements involving the thumb had higher correlation when compared to the formation stage, with moderate values (0.6-0.69) from most participants (Table 4.7). Correlation coefficients between MCP flexion of index, middle and ring fingers were the highest from the movements under analysis. These results suggest the manipulation of the cylinder object required little finger independent movement, particularly from digits 2-5 (Table 4.11).

Release stage: During the release stage of the VDT-Cylinder task, flexion movements across fingers were moderately correlated, with values between 0.6 and 0.85 from 90% of the subjects. Correlation coefficients between the index, middle, and ring fingers MCP flexion had the highest correlation among the movements under analysis. Furthermore, movements involving the thumb had higher correlation coefficients when compared to the formation and manipulation stages, suggesting the release was made of coordinated, interdependent extension from most joints as the hand returned to the resting position (Table 4.7, 4.11, Appendix D).

TABLE 4.7 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM THE MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE VDT-CYLINDER TASK.

	Formation stage			
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Ring
Subject	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.76 (0.059)	0.62 (0.092)	0.58 (0.075)	0.94 (0.035)
2	0.50 (0.081)	0.45 (0.074)	0.69 (0.049)	0.62 (0.051)
3	0.49 (0.073)	0.54 (0.079)	0.61 (0.078)	0.68 (0.074)
4	0.76 (0.085)	0.48 (0.066)	0.61 (0.085)	0.66 (0.063)
5	0.41 (0.092)	0.52 (0.080)	0.63 (0.058)	0.71 (0.083)
6	0.53 (0.067)	0.58 (0.079)	0.62 (0.091)	0.65 (0.077)
7	0.58 (0.071)	0.46 (0.084)	0.57 (0.11)	0.68 (0.091)
8	0.48 (0.082)	0.54 (0.072)	0.51 (0.088)	0.6 (0.059)
9	0.59 (0.064)	0.42 (0.095)	0.58 (0.064)	0.69 (0.062)
	Manipulation stage			
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Ring
	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.78 (0.091)	0.62 (0.085)	0.58 (0.072)	0.81 (0.079)
2	0.76 (0.084)	0.59 (0.091)	0.52 (0.090)	0.85 (0.063)
3	0.85 (0.057)	0.65 (0.070)	0.59 (0.081)	0.79 (0.065)
4	0.78 (0.063)	0.61 (0.049)	0.60 (0.076)	0.82 (0.071)
5	0.81 (0.075)	0.65 (0.058)	0.55 (0.058)	0.88 (0.053)
6	0.87 (0.066)	0.63 (0.073)	0.57 (0.062)	0.82 (0.055)
7	0.85 (0.081)	0.58 (0.085)	0.63 (0.085)	0.85 (0.066)
8	0.89 (0.049)	0.60 (0.062)	0.69 (0.071)	0.84 (0.073)
9	0.82 (0.052)	0.64 (0.092)	0.55 (0.039)	0.78 (0.082)
	Release stage			
	MCP Flexion Index MCP Flexion Middle	MCP Flexion Index MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Thumb	MCP Flexion Middle MCP Flexion Ring
	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)	Mean Correlation Coefficient (+/-S.D.)
1	0.72 (0.091)	0.61 (0.073)	0.64 (0.092)	0.81 (0.072)
2	0.78 (0.053)	0.67 (0.085)	0.57 (0.069)	0.73 (0.068)
3	0.81 (0.064)	0.58 (0.077)	0.63 (0.084)	0.79 (0.089)
4	0.69 (0.085)	0.69 (0.081)	0.62 (0.075)	0.74 (0.075)
5	0.84 (0.051)	0.61 (0.091)	0.60 (0.088)	0.72 (0.055)
6	0.75 (0.059)	0.59 (0.037)	0.63 (0.071)	0.78 (0.063)
7	0.72 (0.062)	0.55 (0.058)	0.68 (0.063)	0.79 (0.084)
8	0.78 (0.083)	0.66 (0.081)	0.66 (0.077)	0.82 (0.070)
9	0.81 (0.058)	0.63 (0.055)	0.61 (0.070)	0.73 (0.052)

Drinking from a glass task

Formation stage: During the formation stage of the glass task, correlation coefficients between MCP flexion from index, middle, and ring fingers were from moderate to high (0.71 – 0.95) for most participants, while correlation from movements involving the thumb and little finger was between low and moderate (0.45 - 0.69). Results and observation suggest the formation of the cylinder grip required to drink from the glass was generally made of coordinated flexion movements, as the fingers prepared for the specific size of the glass (Table 4.8, 4.11).

Manipulation stage: The manipulation stage was characterised by low correlation coefficients from the little finger's MCP, PIP, and DIP flexion (0.1 – 0.4) with respect to the rest of the fingers. Movement from digits 2-4 were moderately or highly correlated across subjects during the manipulation of the glass, indicating the object was firmly under control with coordinated movements from these digits. Additionally, movement correlation from MCP thumb flexion was between 0.5 and 0.7 for most subjects, indicating low to moderate coordination between digits 2-5 and the thumb when holding and transporting the glass (Table 4.8).

Release stage: Correlation coefficients from movements involving the index, middle, and ring fingers were high for most subjects during the release stage of the task (0.8 - 0.95). Thumb flexion movements were moderately correlated with both index and middle fingers for 80% of participants, suggesting the dissolution of the cylinder grasping patterns was mostly made of interdependent finger flexion-extension movements. Moreover, results suggest the drinking task was generally made of well coordinated and interdependent finger movements during its three pre-defined stages (Table 4.8, 4.11, Appendix D).

TABLE 4.8 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM THE MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE DRINKING TASK.

	Formation stage			
Subject	**MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.86 (0.055)	0.67 (0.082)	0.69 (0.059)	0.76 (0.061)
2	0.95 (0.028)	0.46 (0.055)	0.34 (0.062)	0.95 (0.015)
3	0.74 (0.063)	0.54 (0.072)	0.55 (0.079)	0.74 (0.052)
4	0.83 (0.041)	0.59 (0.049)	0.51 (0.060)	0.81 (0.033)
5	0.79 (0.073)	0.48 (0.076)	0.57 (0.084)	0.85 (0.039)
6	0.92 (0.031)	0.62 (0.037)	0.65 (0.073)	0.82 (0.052)
7	0.85 (0.049)	0.53 (0.061)	0.68 (0.051)	0.88 (0.046)
8	0.90 (0.044)	0.64 (0.084)	0.55 (0.080)	0.83 (0.058)
9	0.71 (0.079)	0.49 (0.066)	0.5 (0.037)	0.89 (0.027)
	Manipulation stage			
	MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.91 (0.025)	0.65 (0.073)	0.61 (0.056)	0.86 (0.031)
2	0.83 (0.049)	0.59 (0.052)	0.65 (0.085)	0.83 (0.044)
3	0.88 (0.033)	0.67 (0.079)	0.43 (0.073)	0.93 (0.028)
4	0.93 (0.038)	0.52 (0.085)	0.52 (0.061)	0.79 (0.052)
5	0.89 (0.022)	0.64 (0.082)	0.68 (0.079)	0.88 (0.035)
6	0.85 (0.035)	0.69 (0.058)	0.52 (0.048)	0.84 (0.027)
7	0.79 (0.054)	0.55 (0.091)	0.50 (0.088)	0.92 (0.032)
8	0.94 (0.019)	0.59 (0.075)	0.62 (0.072)	0.95 (0.029)
9	0.73 (0.042)	0.68 (0.070)	0.64 (0.057)	0.82 (0.048)
	Release stage			
	MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.89 (0.024)	0.35 (0.048)	0.72 (0.081)	0.67 (0.070)
2	0.82 (0.045)	0.71 (0.052)	0.63 (0.076)	0.83 (0.061)
3	0.86 (0.039)	0.58 (0.082)	0.66 (0.058)	0.91 (0.034)
4	0.94 (0.026)	0.69 (0.046)	0.69 (0.073)	0.82 (0.041)
5	0.83 (0.047)	0.61 (0.069)	0.60 (0.082)	0.85 (0.062)
6	0.88 (0.051)	0.59 (0.049)	0.63 (0.058)	0.83 (0.026)
7	0.90 (0.031)	0.55 (0.062)	0.68 (0.051)	0.80 (0.036)
8	0.82 (0.047)	0.66 (0.075)	0.45 (0.063)	0.94 (0.024)
9	0.85 (0.050)	0.63 (0.071)	0.64 (0.085)	0.78 (0.039)

Variable Dexterity Test – Spherical

Formation stage: During the formation stage of the VDT-Spherical task the MCP flexion movements of both middle and ring fingers had moderate to high correlation coefficients (0.75 – 0.95). In addition, correlation coefficients between MCP flexion movements of the thumb and index and middle fingers were low to moderate (0.5 – 0.75) suggesting movements from digits 2-5 were made of coordinated flexion-extension as the hand reached forward and extends, forming the required spherical grip (Table 4.9).

Manipulation stage: The manipulation stage of the VDT-Spherical task had high correlation coefficients between movements involving digits 2-5 (0.8 – 0.95) from 90% of participants. Movements involving the thumb had considerably lower correlation coefficients, indicating an independent role of thumb flexion as the hand transports the circular object to the target position while maintaining the spherical posture (Table 4.9).

Release stage: The release stage of the VDT-Spherical task showed a similar pattern of high correlation between digits 2-4, with coefficients ranging between 0.8 – 0.95 in 90% of participants (Table 4.9, Appendix D).

TABLE 4.9 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM THE MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE VDT-SPHERICAL TASK.

	Formation stage			
Subject	**MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.75 (0.039)	0.69 (0.058)	0.85 (0.044)	0.91 (0.032)
2	0.99 (0.010)	0.81 (0.072)	0.80 (0.059)	0.93 (0.029)
3	0.86 (0.042)	0.46 (0.055)	0.50 (0.066)	0.84 (0.052)
4	0.82 (0.049)	0.72 (0.082)	0.59 (0.071)	0.88 (0.027)
5	0.94 (0.023)	0.51 (0.080)	0.71 (0.052)	0.83 (0.048)
6	0.81 (0.038)	0.66 (0.085)	0.62 (0.049)	0.79 (0.041)
7	0.90 (0.029)	0.62 (0.074)	0.69 (0.078)	0.91 (0.019)
8	0.85 (0.037)	0.54 (0.078)	0.52 (0.069)	0.86 (0.053)
9	0.97 (0.012)	0.59 (0.069)	0.72 (0.083)	0.94 (0.021)
	Manipulation stage			
	MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.88 (0.031)	0.24 (0.049)	0.54 (0.061)	0.83 (0.038)
2	0.80 (0.050)	0.64 (0.051)	0.72 (0.084)	0.87 (0.042)
3	0.74 (0.056)	0.68 (0.088)	0.61 (0.073)	0.84 (0.051)
4	0.88 (0.042)	0.63 (0.074)	0.46 (0.087)	0.72 (0.084)
5	0.91 (0.025)	0.59 (0.063)	0.67 (0.081)	0.93 (0.033)
6	0.85 (0.037)	0.68 (0.077)	0.62 (0.065)	0.80 (0.045)
7	0.93 (0.022)	0.57 (0.081)	0.69 (0.047)	0.84 (0.052)
8	0.82 (0.048)	0.61 (0.048)	0.58 (0.089)	0.92 (0.027)
9	0.84 (0.052)	0.64 (0.082)	0.65 (0.058)	0.81 (0.036)
	Release stage			
	MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.91 (0.035)	0.63 (0.072)	0.59 (0.085)	0.95 (0.012)
2	0.83 (0.026)	0.67 (0.055)	0.50 (0.073)	0.91 (0.025)
3	0.62 (0.042)	0.61 (0.091)	0.68 (0.036)	0.71 (0.039)
4	0.85 (0.044)	0.72 (0.048)	0.65 (0.050)	0.97 (0.010)
5	0.89 (0.036)	0.60 (0.082)	0.71 (0.069)	0.81 (0.049)
6	0.95 (0.021)	0.63 (0.059)	0.52 (0.059)	0.85 (0.062)
7	0.88 (0.029)	0.69 (0.068)	0.64 (0.090)	0.89 (0.021)
8	0.80 (0.047)	0.58 (0.081)	0.65 (0.074)	0.92 (0.036)
9	0.83 (0.051)	0.61 (0.045)	0.62 (0.048)	0.87 (0.042)

Jar Opening task

Formation stage: The formation stage of the jar task was made of highly correlated flexion movements of digits 2-4 (0.8 – 0.95). Correlation of flexion movements involving the thumb were moderately correlated across the stage for most participants, suggesting a highly coordinated movement from most subjects whilst forming the spherical grip required to interact with the lid (Table 4.10).

Manipulation stage: During the manipulation phase correlation between relevant movements associated with the spherical grip remained moderate to high (0.6 – 0.95). Index, middle, and ring fingers MCP flexion were particularly high during this stage, with correlation coefficients above 0.8 for 90% of participants. Manipulation of the jar was characterised by interdependent movements of all fingers involved, as the dominant hand had firm control over the lid (Table 4.10, 4.11).

Release stage: Correlation between MCP flexion movements associated with the spherical grip were high across subjects (0.8 – 0.95). Moreover, movements involving the thumb were moderately correlated with the rest of the movements (0.6 -0.75) for 80% of the subjects. These results suggest interdependent and coordinated flexion extension movements, particularly from MCP joints, as the fingers were extending to release the object and the hand returned to the starting position (Table 4.10, 4.11, Appendix D).

Overall, spherical and cylinder grip tasks had higher correlation coefficients across subjects, particularly during the manipulation phase of tasks, where statistically significant (two-sampled t-test, $p < 0.05$) difference was observed between Cylinder-Spherical tasks and Precision tasks (Figure 4.13, Table 4.12).

TABLE 4.10 MEAN VALUES OF THE CORRELATION COEFFICIENTS FROM THE MCP JOINTS FOR ALL SUBJECTS DURING THE THREE STAGES OF THE JAR OPENING TASK.

	Formation stage			
Subject	**MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.82 (0.047)	0.62 (0.055)	0.65 (0.073)	0.93 (0.017)
2	0.96 (0.022)	0.64 (0.039)	0.61 (0.041)	0.96 (0.024)
3	0.85 (0.041)	0.59 (0.024)	0.72 (0.038)	0.91 (0.033)
4	0.91 (0.027)	0.60 (0.082)	0.68 (0.085)	0.85 (0.045)
5	0.82 (0.058)	0.61 (0.077)	0.63 (0.046)	0.71 (0.029)
6	0.79 (0.034)	0.51 (0.046)	0.61 (0.029)	0.82 (0.059)
7	0.87 (0.031)	0.69 (0.035)	0.40 (0.058)	0.91 (0.040)
8	0.84 (0.029)	0.71 (0.021)	0.64 (0.075)	0.83 (0.035)
9	0.94 (0.024)	0.66 (0.065)	0.71 (0.044)	0.88 (0.051)
	Manipulation stage			
	MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.89 (0.042)	0.55 (0.025)	0.51 (0.040)	0.92 (0.022)
2	0.94 (0.028)	0.61 (0.083)	0.41 (0.077)	0.78 (0.051)
3	0.91 (0.049)	0.69 (0.055)	0.67 (0.082)	0.87 (0.064)
4	0.88 (0.030)	0.57 (0.049)	0.69 (0.039)	0.85 (0.072)
5	0.81 (0.058)	0.73 (0.091)	0.60 (0.064)	0.94 (0.013)
6	0.85 (0.034)	0.67 (0.034)	0.63 (0.071)	0.92 (0.032)
7	0.92 (0.021)	0.61 (0.086)	0.69 (0.028)	0.86 (0.047)
8	0.83 (0.052)	0.68 (0.047)	0.54 (0.038)	0.88 (0.021)
9	0.88 (0.032)	0.52 (0.038)	0.58 (0.083)	0.93 (0.044)
	Release stage			
	MCP Flexion Index MCP Flexion Middle Mean Correlation Coefficient (+/-S.D.)	**MCP Flexion Index MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Thumb Mean Correlation Coefficient (+/-S.D.)**	**MCP Flexion Middle MCP Flexion Ring Mean Correlation Coefficient (+/-S.D.)**
1	0.71 (0.025)	0.64 (0.073)	0.51 (0.041)	0.93 (0.039)
2	0.89 (0.042)	0.71 (0.065)	0.65 (0.092)	0.85 (0.015)
3	0.92 (0.027)	0.46 (0.082)	0.69 (0.025)	0.81 (0.056)
4	0.83 (0.056)	0.69 (0.026)	0.63 (0.081)	0.88 (0.032)
5	0.88 (0.052)	0.57 (0.080)	0.42 (0.032)	0.94 (0.037)
6	0.85 (0.071)	0.62 (0.079)	0.59 (0.069)	0.83 (0.051)
7	0.82 (0.065)	0.69 (0.054)	0.47 (0.070)	0.71 (0.082)
8	0.91 (0.033)	0.59 (0.059)	0.68 (0.021)	0.82 (0.074)
9	0.93 (0.026)	0.61 (0.084)	0.62 (0.058)	0.89 (0.024)

TABLE 4.11 MEANS AND STANDARD DEVIATIONS FOR ALL SUBJECTS, ACROSS TASKS' STAGES

	Formation		Manipulation		Release	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
PPBT	0.826	0.051	0.566	0.089	0.867	0.053
VDTP	0.833	0.119	0.627	0.110	0.687	0.072
Button	0.788	0.058	0.698	0.071	0.822	0.100
Coin	0.872	0.038	0.714	0.043	0.794	0.052
Bottle	0.873	0.046	0.842	0.042	0.384	0.091
VDTC	0.567	0.122	0.823	0.045	0.767	0.050
Glass	0.839	0.081	0.861	0.069	0.866	0.041
VDTS	0.877	0.080	0.850	0.059	0.840	0.094
Jar	0.867	0.058	0.879	0.043	0.860	0.068

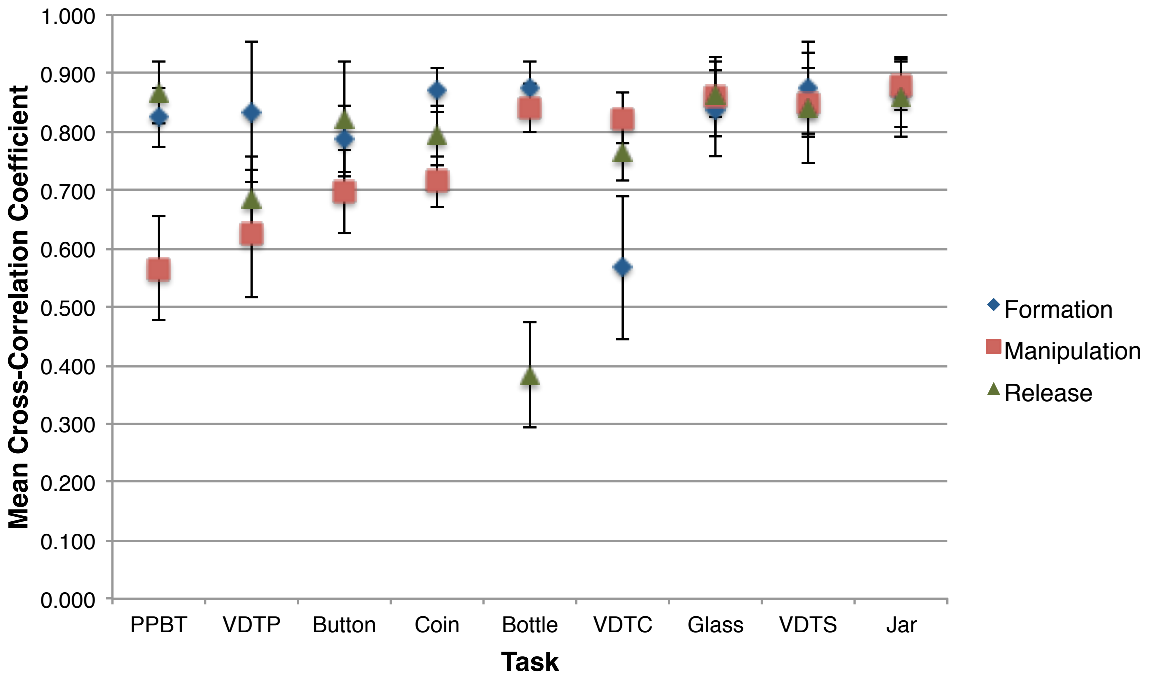


FIGURE 4.13 MEANS AND S.D. ACROSS STAGES. THE MANIPULATION STAGE OF PRECISION TASKS SHOWING LOWER CROSS-CORRELATION AMONG GRASPING PATTERNS

TABLE 4.12 STATISTICAL SIGNIFICANCE (*P* VALUE) OF THE DIFFERENCE BETWEEN CROSS-CORRELATION VALUES BETWEEN GRASPING PATTERNS AND ACROSS STAGES.

Stage	Grasping patterns	p value
Formation	Precision-Cylinder	0.1379
	Precision-Sprerical	0.2641
Manipulation	Precision-Cylinder	**0.0471**
	Precision-Sprerical	**0.0494**
Release	Precision-Cylinder	0.5064
	Precision-Sprerical	0.3827

4.3.4 Summary and discussion

Previous studies have employed various data acquisition techniques and analysis methods to examine finger movement coordination. However, there are just a few comprehensive quantitative descriptions of the movement patterns from a kinematic perspective under multi-finger, multi-joint tasks [23]–[25]. This experimental study was an attempt to contribute to the understanding of dexterity by utilising the latest measurement technology to obtain kinematic data and, at the same time, investigate the robustness of dexterity tests, by comparing finger movement correlation patterns during the performance of the tests with those measured during tasks related to activities of daily living.

Although the complex correlated movements of the hand have been investigated in previous studies, most paradigms have included a very specific set of tasks and grasping patterns, and were not wide enough to assess hand function in a variety of daily living tasks [22], [25], [151], [152]. Moreover, although synergistic movement has been studied during sophisticated uses of the hand, investigations into how movement patterns are assessed by traditional dexterity tests and how it translates into daily living tasks were still lacking.

This study rendered evidence of existing finger correlation patterns during daily living tasks and, particularly, it allowed the quantification of the effects of object size and grasping strategies. Moreover, the study discovered that such correlation patterns are consistent for the selected activities of daily living and dexterity tests.

The tasks selected for this study require the performance of the three most frequently used grip styles according to the literature: Precision, cylinder, and spherical, and the trials were sub-divided into three phases to increase the precision of the analysis and aid in the identification of movement patterns (formation of the grip style, manipulation, and release). Moreover, the analysis of individual task's stages provided evidence of quantifiable reaching, manipulating, and releasing strategies in the pilot group.

Precision grip tasks

During the formation stage of tasks requiring a precision grip, correlation coefficients between the fingers actively involved in the task were consistently high across most subjects, indicating interdependent movement as the index, thumb, and middle fingers flexed and the hand reached forward to grab the object. Correlation coefficients between the thumb and index and middle fingers' movements were generally lower when compared to correlation between movements from the index and middle fingers across tasks. Movements during performance of the Purdue Pegboard Test had the lowest correlation coefficients during the formation phase across subjects, with movements involving the thumb having coefficients below 0.5 across subjects.

The manipulation stage of precision tasks was characterised by lower movement correlation across tasks, with statistically significant differences observed between precision tasks and grosser tasks. Observed increased independent finger movement during the manipulation of smaller objects is in line with previous studies analysing the role of virtual fingers, not in contact with the object, providing stability and balance to the grasping action [25], [59], [153].

Overall, activities of daily living had low correlation coefficients during the manipulation phase, with correlation between movements involving thumb and index and middle fingers being below 0.75 across most participants. Movements during the coin task, however, resulted in moderate to high correlation coefficients across participants, showing coordinated finger movements with values closer to those observed during the formation stage.

Correlation coefficients from the Purdue Pegboard Test were the lowest across tasks and participants, indicating a higher degree of independent movement during the performance of the test when compared to the VDT-Precision and the selection of activities of daily living.

During the release stage, the majority of the precision tasks had low to moderate (0.3 – 0.7) correlation coefficients from the fingers actively involved in the task, suggesting the release of the object and the subsequent return of the hand to the resting posture were made of independent finger movements, particularly from those movements involving the thumb. The release stage of the Purdue Pegboard Test resulted in particularly high correlation coefficients between the index and middle fingers' flexion, with values above 0.90. Finger movement correlation during the VDT-Precision and the selection of activities of daily living were mostly consistent, with thumb and index and middle fingers' flexion movements having the lowest coefficients across participants. These patters may suggest the release phase of precision tasks is made of mostly uncoordinated finger movement, with fingers initiating the release independently as the task is completed, extending and releasing the object.

Cylinder grip tasks

The formation phase of cylinder grip tasks had low to moderate correlation coefficients in movements involving the thumb during both the VDT-Cylinder and the drinking task, while movements involving the index, middle, and ring fingers were moderately to highly correlated across participants and tasks. These patterns may suggest the formation of the cylinder grip as the hand approaches the object is made of independent thumb flexion movements and interdependent movement from the rest of the digits, particularly digits 2-4.

During the manipulation phase, finger movement correlation remained between low and moderate for movements involving the thumb, with coefficients ranging from 0.4 to 0.7, indicating low interdependence in movements involving the thumb, as the had made contact with the object and performed the required task. In general, finger movement during cylinder grip tasks is characterised by high correlation once the object is held, with most fingers in contact with the object forming the cylinder grasp. This pattern however, does not mean all fingers have the same role during cylinder grasping; previous studies have found evidence of pressure and strength differences across fingers during power and cylinder grasping [112], [154]. Correlation coefficients during the VDT-Cylinder and the drinking task showed no statistically significant difference, with the drinking task having higher correlation with respect to the VDT in movements involving index, middle and ring fingers.

Movements involving the thumb had low to moderate correlation coefficients during the release phase, while correlation coefficients between movements from digits 2-4 were between moderate and high. Movement correlation during the drinking task was consistently higher when compared to the VDT task. This pattern may provide additional evidence of the role of task familiarity and learned strategies, although further investigation into the actual role of cognitive and learning aspects of hand function may help better understand these effects, particularly during the release phase, with the task already completed and the hand returning to a resting posture.

Spherical Grip Tasks

The formation stage of tasks requiring the spherical grip had mostly low to moderate correlation coefficients for movements involving the thumb in both the VDT-Spherical and the jar task, however, there were moderate to high coefficients for two subjects performing the VDT. Movements from digits 2-4 had moderate to high correlation coefficients across subjects and tasks. These results suggest the formation phase of both tasks was characterised by interdependent movement from digits 2-4 as they extended to for a spherical grip. Thumb flexion/extension movements has a higher degree of independence when compared to the rest of the fingers. Differences between correlation coefficients from precision and spherical tasks was found to be not statistically significant during this phase, although previous studies have found distinctive reaching patterns depending on object shape and task [58], [59], [82]. An extended analysis from larger populations may help identify such differences from a movement correlation point of view.

The manipulation phase of spherical tasks had high correlation coefficients between movements involving the index, middle, and ring fingers, while correlation coefficients from movements of the thumb were low across tasks and subjects. These pattern indicates coordinated finger flexion of digits 2-4 as they extended to form the spherical grip. Movements from the thumb are significantly more independent, as seen from the coefficients ranging from 0.2 - 0.5 for most subjects. Manipulation of spherical objects was generally characterised by most fingers being in contact with the object, resulting in limited and coordinated movement. Two-samples t-test showed statistically significant differences between spherical and precision grip correlations during this stage, further evidencing the different role of fingers depending on object size and shape. Digits 3-5 interacting with small objects tend to work as stabilizers, not in direct contact with the object. This behaviour has been identified as virtual finger, two or three digits working independently providing balance during the grasping action [77], [87], [88].

During the release phase both tasks had low to moderate correlation between movements involving the thumb, with values ranging from 0.5-0.7, reaching higher values when compared to the formation and manipulation stages. Correlation between movements of index, middle, and ring fingers were consistently high across subjects during the VDT-Spherical, while during the jar opening tasks values ranged between moderate and high (0.7-0.9). Results from the release phase indicate finger extension after a spherical grasp is mostly made of coordinated movements from digits 2-4. Although differences between spherical and precision tasks during this phase were shown to be statistically not significant, correlation coefficients were lower during precision tasks. Further investigation into this behaviour with larger samples may provide statistical evidence of differences during the release phase across tasks.

In conclusion, the identified correlation patterns across all the tasks' stages seem to suggest a relation exists between object size, grip style, and finger interdependencies, with tasks requiring fine manipulation of smaller objects in reduced volumes resulting in low finger movement correlation, as fingers moved in distinctive patterns to form the optimal grasping pattern, grab and control the object, and complete the task. The role of fingers not in contact with the object, particularly during precision tasks, was shown to be relevant for optimal control during the manipulation phase, providing balance during object transport and execution of tasks. This pattern is in line with previous works on the role of virtual fingers in reaching and grasping. Furthermore, tasks requiring cylinder and spherical grip styles consistently resulted in higher correlation coefficients across movements of digits 2-4, indicating manipulation of larger objects generally require interdependent finger flexion/extension, with most fingers in contact with the object during the manipulation phase.

In addition, results from the analysis of finger movement correlation of the VDT were comparable to those from related activities of daily living across grip styles, suggesting the subtests that make the Variable Dexterity Test may reflect the role of finger interdependencies in the performance of tasks requiring the precision, cylinder, and spherical grip styles.

The analysis of finger movement correlation showed potential as a tool to accurately visualise and quantify independent finger roles during manipulative tasks. Moreover, it proved to be a viable method to analyse individual tasks stages, rendering evidence of the variety of movement patterns that account for dexterous movements in reaching, grasping, and releasing. The potential use of colour maps to visualise correlation patterns needs further exploration as a dissemination tool, aiming to provide direct evidence of movement patterns across tasks and subjects.

Limitations of this study are mostly due to sample size, with further investigation needed to test validity and reliability of the approach. A comparative analysis with other movement variability techniques may provide additional evidence on the validity of this analysis.

The following chapters of this dissertation will explore the concept of kinematic synergies and trajectory smoothness, in order to further investigate the importance of finger coordinated movements in manipulative tasks, looking to test the viability of these approaches.

4.4 Principal Component Analysis of Finger Movement

4.4.1 Introduction

In most of studies of hand movements, principal component analysis (PCA) has been applied to identify the patterns that rule most of the correlated rotation of multiple degrees of freedom by reducing the dimensionality of the movements to a much smaller number of principal components (PCs) [12], [124], [127].

These combination of anatomical factors that form coordinated joint movements are often referred to as *kinematic synergies*, simultaneous co-variations in independent mechanical degrees of freedom. Kinematic synergies have been shown to occur during daily living manipulative movements of the hand, in a wide range of postures and grasping patterns [24]–[26].

This section explores principal components of manipulative tasks by examining whether synergies can be used to differentiate and identify individual grip styles. Furthermore, the role of kinematic synergies in a variety of dexterous tasks and dexterity tests will be studied, aiming to establish relationships between particular components and types of tasks. A third objective of this study is the evaluation of timed dexterity tests when comparing movement patterns between tests and related activities of daily living.

Moreover, results from this study will be analysed together with results from the cross-correlation study looking to validate the identified movement patterns and their relation with performance of both tests and daily living tasks.

4.4.2 Data Analysis

In order to identify and assess the kinematic synergies, PCA was applied to the instantaneous joint angles of the three previously defined tasks stages: formation, manipulation, and release.

The underlying idea behind principal component analysis is the reduction of the dimensionality of the original data set, while retaining as much as possible the original variation in the data. This reduction is based on transforming the original variables to a newly defined set, named principal components, ordered in a way such that the first few will account for the larger variation present in all of the original variables. Furthermore, principal components allow the approximate description of any grasping pattern by a small set of coefficients, with different patterns having different coefficients, therefore comparisons can be made through simple numerical comparisons.

When 2 angles are simultaneously measured, they are linearly related, meaning both angles must lie on a line. Based on that principle, from a set of measurements involving more than 2 angles at each time, data points are linearly related because they all lie on a plane. Linearly related data sets are redundant because one of the angles can be inferred from the others based on the equation of a line or plane, which is specified by a set of numerical coefficients or weights.

Following these principles, data simplification can be achieved from 3 observed angles (x(t), y(t), z(t)) by approximating their linear relationship (since the data points X lie approximately in the same plane). The numerical equation of the plane and its coefficients define new variables (x(t), z(t)), describing a reduced data set X* within such plane. The new reduced data set X* behaves similarly to X because the original data set was close to the plane. A series of measured angles with this type of linear relationship can then be reconstructed as data set that involves fewer variables. In addition, because of the previously explained redundancy of joint angles data sets, errors from this simplification are often very small.

The instantaneous joint angles obtained from motion capture data from participants performing the selection of activities of daily living and dexterity tests were used as original data set X, where each row represents a measured joint angle, and each column represents a subject:

$$\boldsymbol{X} = \begin{bmatrix} IndexMCPFlexion_1 & \cdots & IndexMCPFlexion_p \\ \vdots & \ddots & \vdots \\ ThumbAbduction_1 & \cdots & ThumbAbduction_p \end{bmatrix}$$

Principal components were computed by subtracting from the joint angles matrix X the average of its values and then dividing by the standard deviation, then evaluating its covariance matrix:

$$\boldsymbol{\Sigma} = \frac{\boldsymbol{1}}{\boldsymbol{n-1}} \boldsymbol{X^T X} \tag{7}$$

Σ is then decomposed according to:

$$\boldsymbol{\Sigma} = \boldsymbol{U \overline{\Sigma} V^T} \tag{8}$$

where $\bar{\Sigma}$ is diagonal and contains the eigenvalues of Σ. The columns of U are rearranged in decreasing order according to the magnitude of the eigenvalues, so that each of these columns, when applied back to X, produces a linear combination of the dimensions of X. Denoting by U_k the $k \times n$ sub-matrix of U obtained by selecting only the first k columns of U,

$$\boldsymbol{X}^{*} = \boldsymbol{U_k X} \tag{9}$$

is a k-dimensional projection of X onto a space with the maximal fraction of the signal variance in X. From the sum of the eigenvalues of Σ, the lost signal variance can be estimated as k is increased until $k = d$. The principal components of X can then be defined as each of the resulting k dimensions. For the purposes of this analysis, principal components of the instantaneous joint angles denote kinematic synergies.

4.4.3 Results

Formation Phase

Scree plots of variance explained, containing the percent variance explained by the corresponding principal component, were computed in order to visualise the number of synergies that account for each selected task. These scree plots only show principal components that explain a cumulative 95% of the total variance, with the blue line indicating cumulative variance.

During the formation phase of the precision tasks, both dexterity tests showed 5 principal components accounting for up to 10% of the movement variance, while tasks related to activities of daily living showed a less dispersed distribution of variance, with only 2 and 3 components accounting for at least 10% of the variance respectively (Figure 4.14). There is a clear break in the amount of variance accounted for by each component between the first and second components in both of the activities of daily living, with the first component by itself explaining over 70% of the variance. The formation phase of dexterity tests was characterised by large contribution from digits 1,2,4 and 5, as shown by the first component's coefficients. There was no clear pattern between activities of daily living, as the coin task had significant contributions from digits 1, 4 and 5, while the buttoning task had contributions from digits 1,2, and 3 (Figure 4.14).

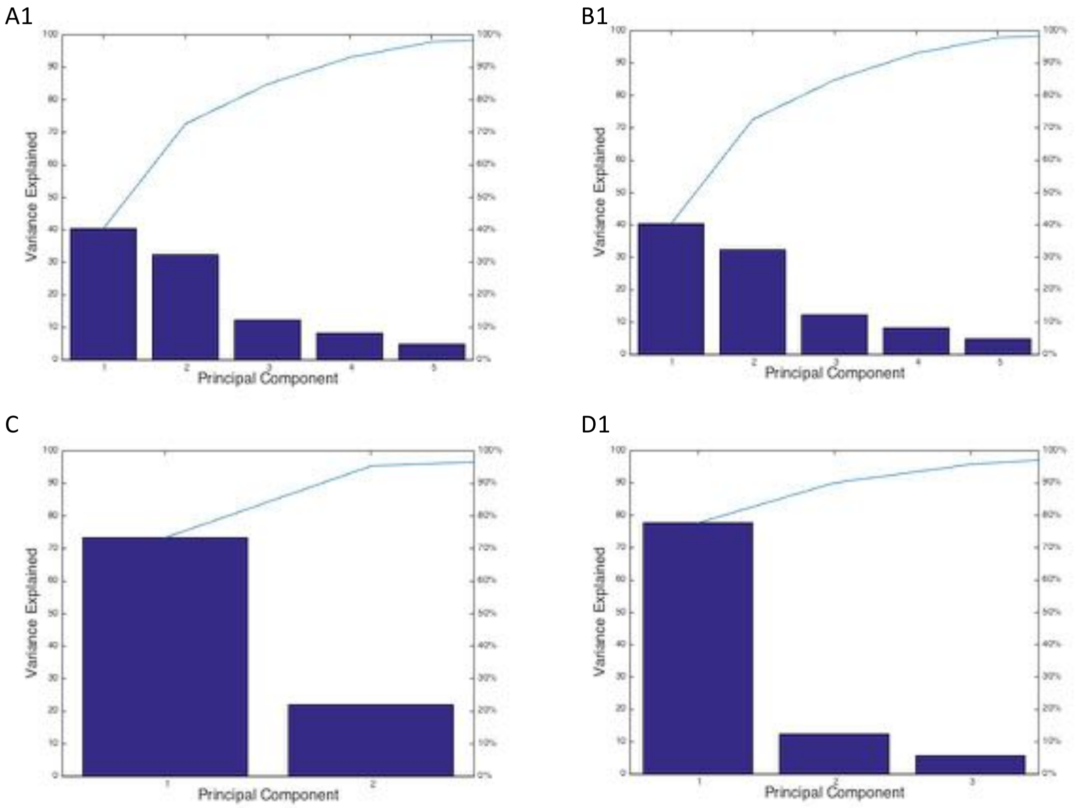


FIGURE 4.14 FORMATION STAGE: PRINCIPAL COMPONENTS ON PRECISION GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) PURDUE PEGBOARD TEST, B) VDT-PRECISION, C) PICK UP COIN TASK, D) BUTTONING TASK.

The formation stage of cylinder grip tasks had two principal components accounting for over 80% of the variance, with components 3 to 5 accounting for less than 10% in both VDT-Cylinder and the drinking task. Additionally, principal components coefficients indicate significant contribution to the overall movement from digits 1 and 2 in both tasks for PC1 (Figure 4.15).

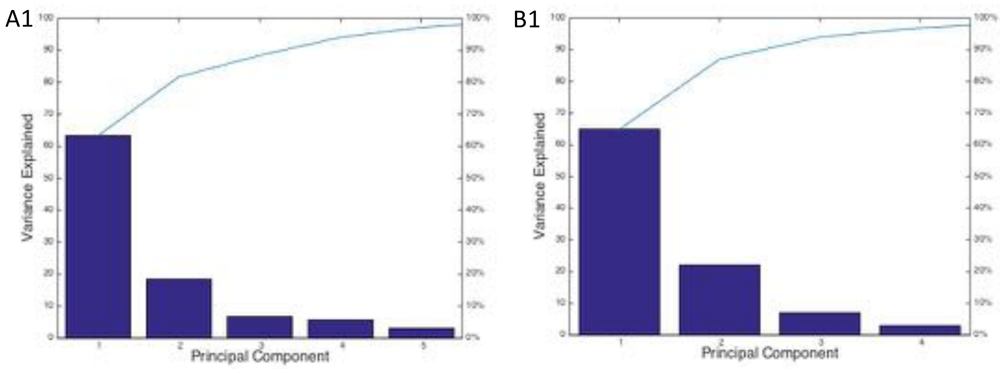


FIGURE 4.15 FORMATION STAGE: PRINCIPAL COMPONENTS ON CYLINDER GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) VDT-CYLINDER B) DRINKING TASK.

During the formation stage of spherical grip tasks, the first principal component accounted for over 70% of the variance in both the VDT-Spherical and the jar opening task. Particularly, the first principal component of the VDT-Spherical task accounted for over 80% of the variance, indicating a significant degree of synergistic movement during the first phase of the task. Principal components' coefficients showed significant contribution from most movements under analysis during the VDT-Spherical, however, the role of the middle finger was considerably larger than the rest of the fingers during for the jar task (Figure 4.16).

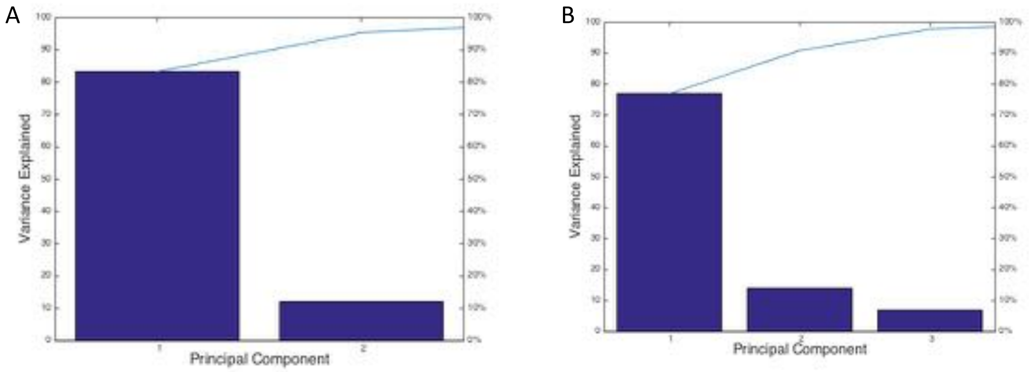


FIGURE 4.16 FORMATION STAGE: PRINCIPAL COMPONENTS ON SPHERICAL GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) VDT-SPHERICAL B) JAR OPENING TASK.

Manipulation Phase

The manipulation stage of precision grip tasks was characterised by two and three principal components accounting for over 10% of the variance. This trend was observed during both dexterity tests and activities of daily living, with the second principal component accounting for over 20% in all precision tasks, indicating a larger degree of independent movement when compared to the formation phase of the same tasks. Independent movement patterns can be observed from data from the principal components' coefficients, where significant contribution is evident from most digits during performance of the dexterity tests, and large contributions from the index and middle fingers during performance of the selected activities of daily living (Figure 4.17).

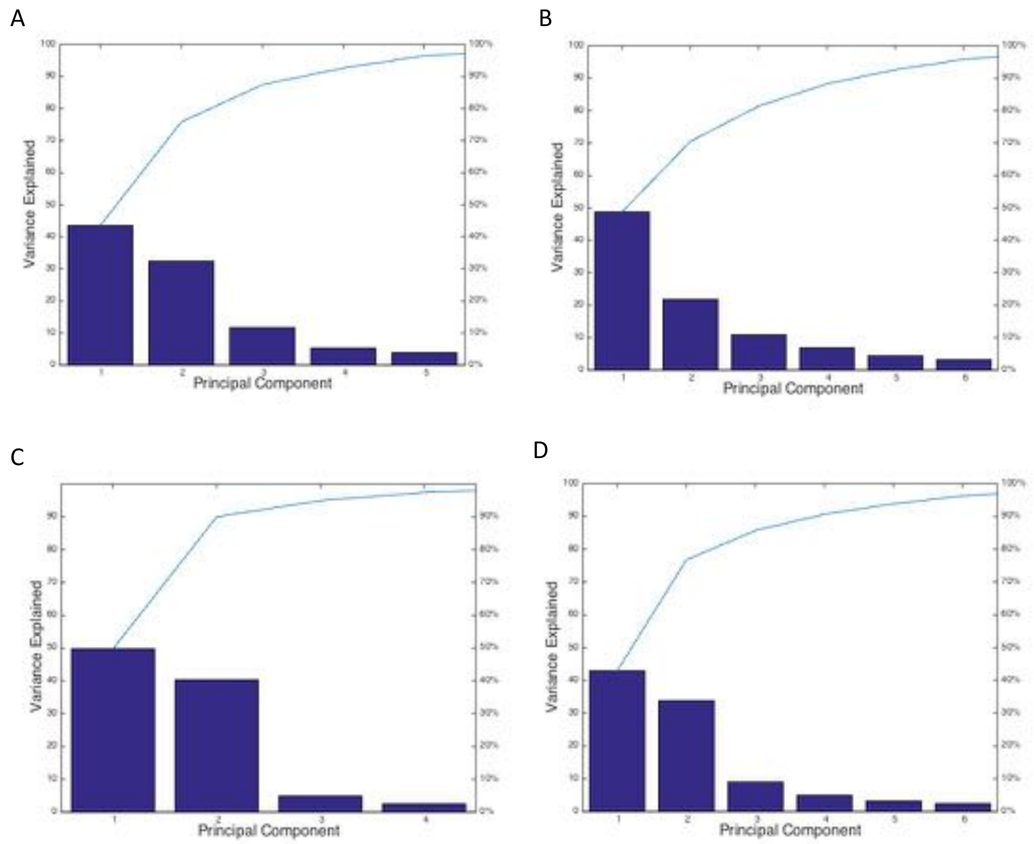


FIGURE 4.17 MANIPULATION STAGE: PRINCIPAL COMPONENTS ON PRECISION GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) PURDUE PEGBOARD TEST, B) VDT-PRECISION, C) PICK UP COIN TASK, D) BUTTONING TASK.

During the manipulation phase of the selection of cylinder grip tasks the first principal component accounted for over 60% of the variance, with a clear break in the amount of variance accounted for between the first and second components in both tasks. This pattern indicates a significant degree of interdependencies between the movements under analysis for this stage of the tasks. Moreover, the coefficients from the first principal component showed significant contributions from most of the movements under analysis. In particular, the VDT-Cylinder task had the largest contributions from the ring and middle fingers, while the largest contributors in the drinking task were middle and index fingers (Figure 4.18).

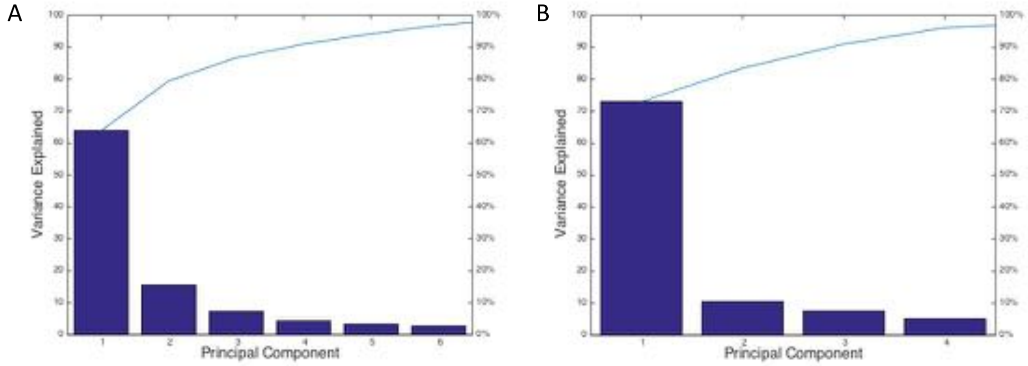


FIGURE 4.18 MANIPULATION STAGE: PRINCIPAL COMPONENTS ON CYLINDER GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) VDT-CYLINDER, B) DRINKING TASK

The manipulation phase of the selection of spherical grip tasks was characterised by a first principal component accounting for over 60% of the variance, with the second component accounting for less than 10%, indicating a high level of interdependence for the movements under analysis. In addition, the coefficients from the first principal component showed large contribution from digits 1, 2 and 5 during the VDT-Spherical task, and significant loadings from all degrees of freedom during the jar opening task (Figure 4.19).

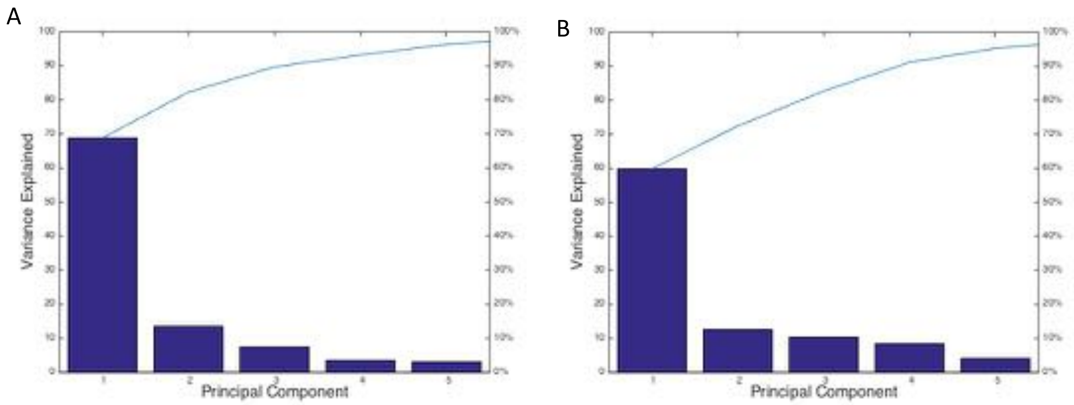


FIGURE 4.19 MANIPULATION STAGE: PRINCIPAL COMPONENTS ON SPHERICAL GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC.. A) VDT-SPHERICAL, B) JAR OPENING TASK

Release Phase

Precision grip tasks had two principal components accounting for over 15% of the variance during the release phase. A clear break could be observed from the first principal component to the second in the Purdue Pegboard Test, the VDT-Precision, and the pick-up coin task, however, the break was significantly smaller in the buttoning task, with the second principal component accounting for over 25% of the variance. Principal components' loadings reflected variable contributions from the degrees of freedom under analysis. Contributions to the first principal component were low from most movements during the dexterity tests when compared against contributions from the activities of daily living, with no clear pattern during this stage (Figure 4.20).

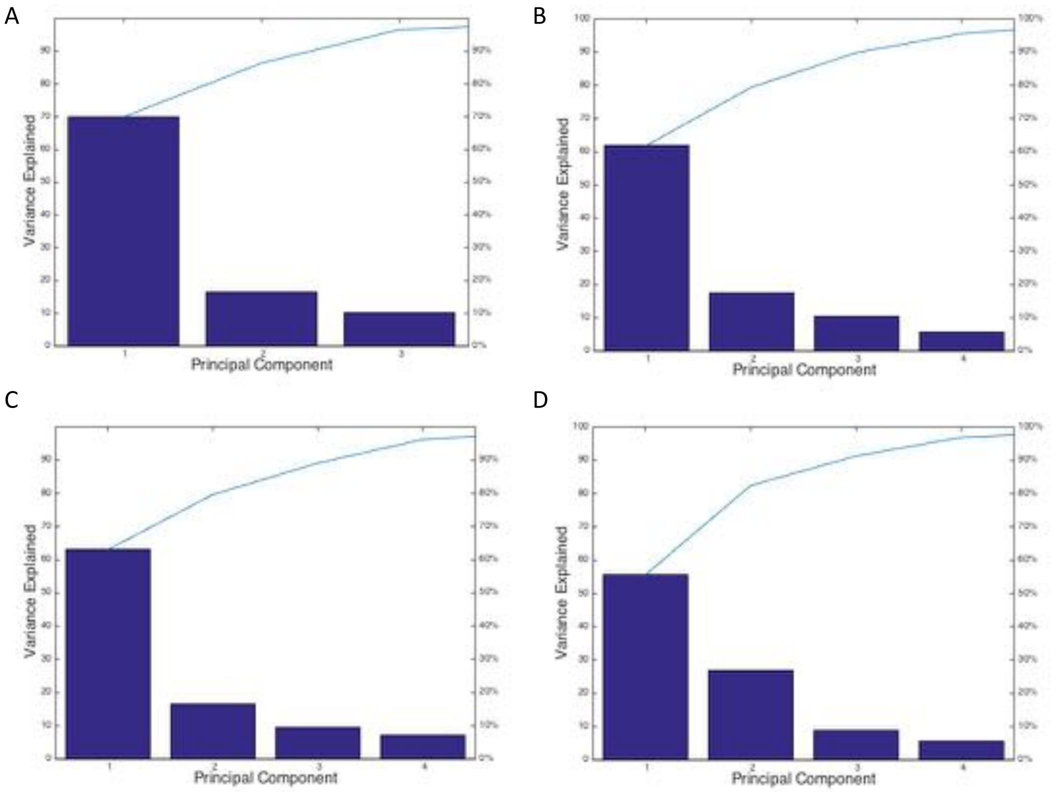


FIGURE 4.20 RELEASE STAGE: PRINCIPAL COMPONENTS ON PRECISION GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) PURDUE PEGBOARD TEST, B) VDT-PRECISION, C) PICK UP COIN TASK, D) BUTTONING TASK.

During the release phase of the cylinder grip tasks the first principal component accounted for 60% or less of the variance, as seen in the scree plots below. The drinking task had the first two principal components accounting for 41% and 38% respectively, with a clear break in the third component, which accounted for less than 10% of the variance. Additionally, the principal components' loadings showed no evident pattern when comparing results from the VDT-Cylinder and the drinking task, with contributions from movements varying widely from one task to another (Figure 4.21).

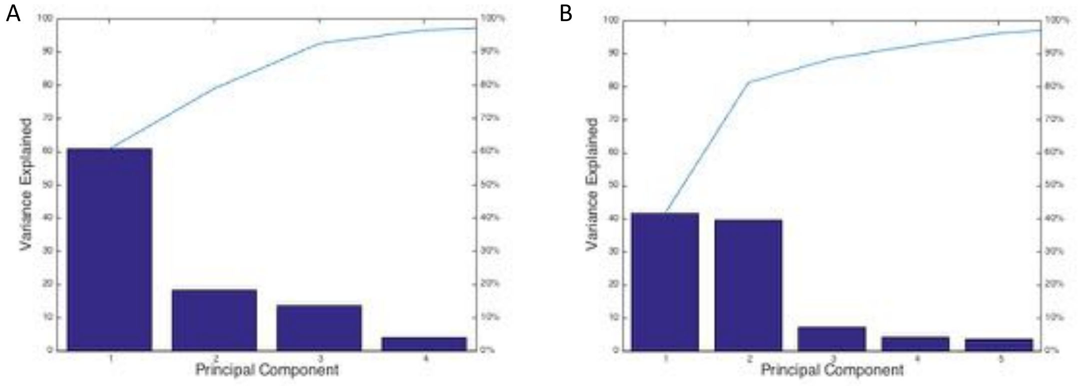


FIGURE 4.21 RELEASE STAGE: PRINCIPAL COMPONENTS ON CYLINDER GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) VDT-CYLINDER, B) DRINKING TASK

The VDT-Spherical had the first principal component accounting for over 70% of the variance during the release phase, with the next principal component accounting for 20%, while the opening jar task had a smaller break between the first and second principal components, with PC1 accounting for 48% of the variance, PC2 accounting for 30%, and PC3 accounting for 15%. Principal components coefficients suggest a similar release movement pattern for both tasks, with thumb and index finger movements having the larger contributions to overall movement, as seen in the bar plots below (Figure 4.22).

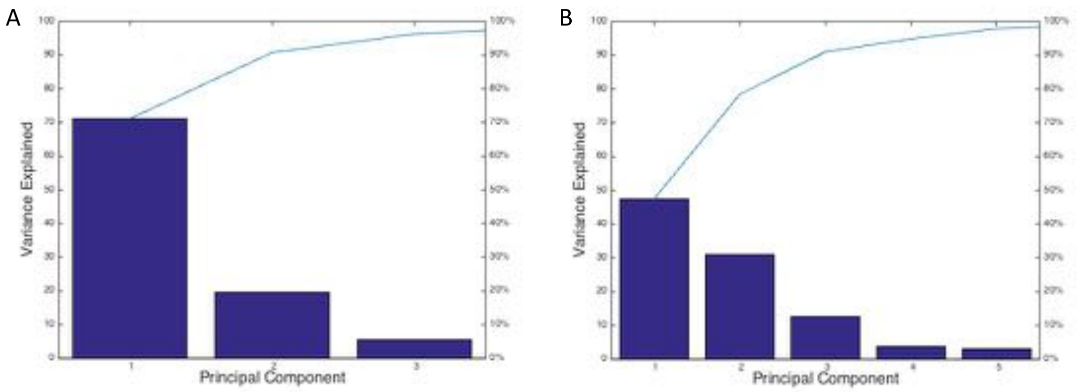


FIGURE 4.22 RELEASE STAGE: PRINCIPAL COMPONENTS ON SPHERICAL GRIP KINEMATICS. SCREE PLOTS OF PERCENTAGE OF EXPLAINED VARIANCE BY REPRESENTATIVE PC. A) VDT-SPHERICAL, B) OPENING JAR TASK

4.4.4 Summary and Discussion

This experimental pilot study was aimed at examining how joint flexion across digits combine as synergies during the performance of both daily living tasks and timed dexterity tests requiring the three most frequently used grasping patterns: precision, cylinder, and spherical grips. In order to investigate this the tasks were split into three underlying phases of manipulative movements: formation, manipulation, and release. Furthermore, the role of individual movements into the kinematic synergies and dexterous movements was studied, aiming to establish relationships between particular components and types of tasks.

Precision grip tasks

During the formation phase, there were variable principal components patterns across precision tasks, with both precision grip tests having principal components 1 to 5 accounting for at least 8% of the movement variance, while daily living tasks had 2 and 3 components accounting for 10% of the variance. The buttoning task in particular, had PC1 accounting for more than 75% of the variance, indicating a larger degree of synergistic movement, as one variable is enough to explain over 70% of the movement. Results from the dexterity tests suggest at least two principal components are required to explain 70% of the variance, reflecting more independent movements were required to form the precision grip. Moreover, coefficients for PC1 in daily living tasks showed no clear pattern, with contributions from movements varying across fingers and tasks.

Results from the manipulation phase of precision grip tasks indicate independent movement across tasks and fingers, with two and three PC's needed to explain 70% of the movement variance. This trend could be observed for both ADL's and dexterity tests, with PC3 accounting for 10% of the variance in most tasks. Furthermore, these results suggest the 15 variables under analysis may be mostly explained by two and three dimensions. Independent movement patterns can also be suggested from data from the loading corresponding to PC1 and PC2, where significant contribution is evident from most digits during performance of the dexterity tests and daily living tasks, indicating proficient manipulation of small objects and finer tasks may require independent finger flexion.

The release stage of precision grip tasks had two principal components accounting for over 15% of the variance and a clear break from the first principal component to the second in the Purdue Pegboard Test, the VDT-Precision, and the pick-up coin task, indicating interdependent movement as the object was released, with one dimension being enough to explain over 65% of the movement variance. The buttoning task however had larger independence across movements, as seen by the significantly smaller break, with the second principal component accounting for over 25% of the variance. Principal components' loadings reflected variable contributions from the movements under analysis. These results may indicate coordinated and interdependent finger extension as the object was released and the hand returned to the resting posture.

Cylinder grip tasks

Principal components analysis of the formation stage of cylinder grip tasks indicates synergistic and interdependent finger movements with PC1 accounting for over 65% of the variance in both the VDT-Cylinder and the drinking task. There is a clear break from PC1 to PC2, with PC2 accounting for 20% of he variance and PC3 accounting for less than 10%. Moreover, principal components' coefficients further suggest interdependent movement as the hand extended to form the cylinder grip, with contribution to PC1 evenly distributed across fingers, and the larger contribution being that from digits 1 and 2 in both.

During the manipulation phase the large variance accounted by the first principal component and the clear break in the amount of variance accounted for after PC1 in both tasks indicate synergistic finger flexion/extension movements as the hand interacted with the cylinder object. Furthermore, the regular contribution pattern shown by components from PC1 suggest the manipulation phase of cylinder tasks was made of coordinated movement from digits 1-5, maintaining a stable posture while the object was transported.

The release phase of the cylinder grip tasks was characterised by the first principal component accounting for 60% or less of the variance, and PC2 accounting for over 20% of the variance. The larger number of variables required to explain finger flexion/extension may suggest independent movements during the dissolution of the cylinder grip. Additionally, the principal components' loadings showed significant contributions from most movements under analysis as the hand extended and returned to the resting posture.

Spherical Grip Tasks

The formation phase of spherical grip tasks had synergistic movements in both tasks according to principal components analysis, with PC1 accounting for over 70% of the variance in both the VDT-Spherical and the jar opening task. Principal components' coefficients further suggested this interdependent movement pattern, as most movements contributed significantly to the formation of the spherical posture as the hand approached the spherical object.

During the manipulation phase, spherical grip tasks had synergistic PC patterns, with clear breaks between PC1 and PC2, and PC1 accounting for more than 60% of the variance. Additionally, individual movements contributions to PC1 further suggest this interdependent movement pattern in both the VDT-Spherical and the jar opening task, as shown by digits 4 and 5 having larger contribution to overall movement as fingers remained extended while manipulating the jar lid and the VDT-Spherical bit.

Results from the release phase of the VDT-Spherical continued the trend of synergistic finger movement seen in previous phases, with the first principal component accounting for over 70% of the and PC2 accounting for less than 20%. The release phase of the jar opening task, however, had PC1 and PC2 accounting for more than 30% individually, indicating a greater degree of independence from the degrees of freedom under analysis. Moreover, PCA's coefficients showed a significant contribution of the thumb and index finger in both tasks as the fingers released the object and went back to the resting posture.

Findings from this study suggest kinematic synergies can be used to identify finger movement patterns during manipulative tasks, particularly during the manipulation phase of tasks. Additionally, it was shown that the number of synergies accounting for manipulative movements is dependent on object size and, thus, grip style, with identifiable principal components patters for the three grasping patterns under analysis. Furthermore, these results show the viability of this approach to study the effects of independent finger movement into the reaching, grasping, and releasing phases of manipulative tasks. Identified movement patterns may help to build on previous efforts regarding development of grasping strategies, with identifiable kinematic synergies for specific grasping patterns and tasks.

The role of virtual fingers on grasping classification and hand function may be further explored with this approach, providing data on the contribution of individual fingers and virtual fingers to the performance of grasping actions [77], [87], [88]. PCA showed increased level of finger independence in precision tasks during the manipulation phase, mainly due to the independent movement of fingers not in direct contact with the object. Moreover, information from finger interdependencies and kinematic synergies during the formation and release phases provides insight on the development of grasping strategies, with quantifiable data on patterns of grasp formation and dissolution. An accurate description of these strategies may help to further enhance our understanding on the development of grasping through learning and experience, by analysing individual phases of manipulative tasks and conducting comparative analyses across populations. Further development of PCA analysis of manipulative tasks must involve larger samples across age ranges and hand function conditions, looking to generate validity and reliability data on independent finger movement.

In conclusion, findings from this experimental study are compatible with previous studies, providing evidence that combinations of a small number of kinematic synergies allows for the reconstruction of an entire set of kinematic variables [12], [24], [125].

Additionally, most studies have been focused either on static postures or complex movements, but an investigation into these kinematic synergies during daily living tasks and their relation with synergies found in dexterity tests had yet to be made. Results from the three pre-defined phases of the tasks are also consistent with studies classifying stages of manipulative hand movements [26], [28], with clear identifiable movement patterns at formation, manipulation and release stages.

Differences across tasks' phases will be further explored in the following section of this dissertation by making use of trajectory analysis in order to further identify the underlying factors that account for hand dexterous movements.

4.5 Trajectory Analysis of Finger Movement

4.5.1 Introduction

This section presents an experimental study of the three-dimensional trajectory of finger movements, aiming at evaluating the reliability of smoothness metrics as measures of hand function and dexterity, as well as compare trajectory metrics between dexterity tests and activities of daily living.

Quality of trajectory, measured as movement smoothness, has been used as a kinematic variable indicative of motor performance of both healthy subjects and persons with motor control and musculoskeletal impairments [30]–[32], [42]. Although smoothness metrics have often been based on minimizing jerk, the rate of change of acceleration, [33], many other measures are possible, including three-dimensional curvature, and the number of peaks in speed profiles [34]–[37]. Smoothness metrics have been used to assess arm ataxia [36], Parkinson's disease [38], children with cerebral palsy [39], and, more generally, it has been shown to account for the two-thirds power law, widely considered an invariant in human movement [40], [41].

Previous works in patients recovering from stroke and other motor related impairments revealed a reduction in trajectory smoothness and segmentation of continuous movements [34], [42]. However, evidence of discrete sub- movements has also been found in the movements of healthy subjects [43], and decomposition of complex movements into sub-movements has been implemented as analysis tool as they account for many patterns in human movement [44].

Moreover results from previous studies have shown that dimensionless jerk metrics accurately reflect changes of movement shape, independent of amplitude and duration, truly reflecting common sources of lack of smoothness such as speed peaks or periods of arrest [42], [155], [156].

In this study, two different measures of movement smoothness were obtained; dimensionless jerk metric [30] and normalized mean speed metric [42], from participants performing representative activities of daily living and dexterity tests. The reliability of the obtained smoothness measures was then analysed as well as their relationship with scores from the Purdue Pegboard Test and the Variable Dexterity Test.

4.5.2 Data Analysis

The analysis consisted of the computation of the magnitude of the velocities, accelerations, and jerk by two-point numerical differentiation of positional data.

Jerk at each time point was computed according to the following equation,

$$J = \left(\dddot{x}^2 + \dddot{y}^2 + \dddot{z}^2 \right)^{1/2} \tag{7}$$

For the measure of the shape of movement to be independent of duration and amplitude, it must be dimensionless. The integrated squared jerk (isJ) has dimensions of length squared divided by the fifth power of time, L^2/T^5:

$$isJ = \int_{t_1}^{t_2} \dddot{x}(t)^2 \, dt \tag{8}$$

Hence, a dimensionless squared jerk (normalized jerk metric) measure is:

$$\boldsymbol{NJM} = \left(\int_{t_1}^{t_2} \dddot{\boldsymbol{x}}(\boldsymbol{t})^2 \boldsymbol{dt} \right) \boldsymbol{D}^5 / \boldsymbol{A}^2 \tag{9}$$

where A is movement amplitude or extent and $D = t_2 - t_1$ is duration.

Because mean speed is the ratio of movement amplitude to duration, $v_{mean} = A/D$, the jerk measure (Normalized Jerk Metric NJM) could be rewritten as:

$$\boldsymbol{NJM} = \left(\int_{t_1}^{t_2} \dddot{\boldsymbol{x}}(\boldsymbol{t})^2 \boldsymbol{dt} \right) \boldsymbol{D}^3 / \boldsymbol{v}_{\boldsymbol{peak}}^2 \tag{10}$$

The normalized speed metric (NSM) was calculated as the mean of the speed divided by the peak speed:

$$\boldsymbol{NSM} = \frac{\boldsymbol{v}_{\boldsymbol{mean}}}{\boldsymbol{V}_{\boldsymbol{peak}}} \tag{11}$$

The resulting speed profile from a non-smooth movement has a series of peaks with deep valleys in between, representing sudden stops between sub-movements (Figure 4.23).

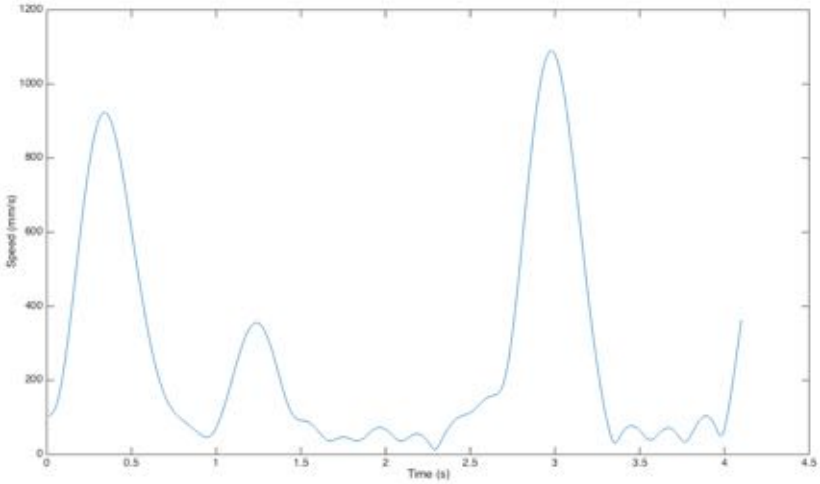


FIGURE 4.23 SPEED PROFILE FROM ONE SUBJECT PERFORMING THE PURDUE PEGBOARD TEST. PEAKS AND VALLEYS INDICATE SUDDEN STOPS BETWEEN SUB-MOVEMENTS DURING TASK PERFORMANCE. THE SPEED METRIC IS A MEASURE OF THE AMOUNT OF SUDDEN STOPS DURING MANIPULATIVE TASKS.

The mean speed of such a movement is much less than its peak, making the normalized mean speed relatively low. A smooth movement tends to have fewer sub-movements and thus, fewer sudden stops, resulting in significantly higher normalized mean speeds.

The statistical analysis consisted of paired samples *t* tests to compare changes in each of the smoothness metrics between tasks' stages across subjects. In addition, the three most frequently used grasping patterns (precision grip, cylinder grip, spherical grip) were compared to each other through two-sampled t-test, looking to identify smoothness patterns and sources of variability across the manipulation stage of tasks. Both T-tests were performed at the 5% significance level ($p < 0.05$).

4.5.3 Results

Formation Stage

The jerk and speed metrics values for the subjects across tasks are shown in tables 4.13 and 4.14.

The formation phase of manipulative tasks was characterised by jerk values below 1×10^6 for most subjects and tasks. Moreover, there was no significant difference between tasks and grip styles, with participants employing similar approaching strategies and no evident difference in smoothness measured by normalized jerk.

Subjects had speed metric values between 0.2 and 0.7 for most tasks during the formation stage, with no significant differences between tasks and grip styles. Subject 1 had the greatest jerk metric and lowest speed metric values, suggesting a low level of smoothness when compared with the rest of participants across tasks.

TABLE 4.13 NORMALIZED JERK METRICS ACROSS SUBJECTS AND TASKS. FORMATION STAGE

	Bottle opening	Buttoning	Pick-up coin	Purdue Test	VDT-Precision	Drinking	VDT-Cylinder	Jar opening	VDT-Spherical
S1	4.04E+05	5.54E+06	1.37E+05	1.39E+05	1.77E+06	1.56E+06	2.03E+06	4.04E+05	5.17E+05
S2	9.89E+04	2.29E+05	1.15E+05	3.60E+05	1.18E+06	4.36E+05	3.37E+04	6.26E+05	5.02E+04
S3	4.07E+05	8.40E+04	1.28E+05	1.54E+05	5.18E+05	3.27E+05	1.75E+05	6.22E+05	2.91E+05
S4	1.46E+05	8.47E+04	3.94E+04	2.97E+05	2.92E+05	6.11E+04	8.21E+04	1.57E+05	5.15E+04
S5	1.71E+05	2.22E+05	3.76E+05	1.66E+06	4.38E+05	6.17E+05	2.41E+05	3.62E+05	1.84E+05
S6	9.32E+04	9.74E+04	5.00E+04	1.65E+05	3.11E+05	1.44E+05	7.73E+04	3.79E+05	5.05E+04
S7	2.34E+05	6.37E+05	1.07E+05	3.23E+05	1.11E+06	4.93E+05	2.46E+05	3.63E+05	1.34E+06
S8	3.63E+05	5.87E+05	1.81E+05	6.12E+05	9.07E+05	2.96E+05	2.62E+05	1.39E+05	3.10E+05
S9	2.92E+05	3.26E+05	2.04E+05	4.91E+05	8.29E+05	4.92E+05	2.06E+06	1.73E+05	4.20E+05
Mean	**2.45E+05**	**8.68E+05**	**1.49E+05**	**4.67E+05**	**8.17E+05**	**4.92E+05**	**5.79E+05**	**3.58E+05**	**3.57E+05**
SD	**1.26E+05**	**1.77E+06**	**1.01E+05**	**4.75E+05**	**4.87E+05**	**4.39E+05**	**8.37E+05**	**1.83E+05**	**4.05E+05**

TABLE 4.14 NORMALIZED SPEED METRICS ACROSS SUBJECTS AND TASKS. FORMATION STAGE

	Bottle opening	Buttoning	Pick-up coin	Purdue Test	VDT-Precision	Drinking	VDT-Cylinder	Jar opening	VDT-Spherical
S1	3.84E-01	2.81E-01	5.18E-01	4.97E-01	2.80E-01	4.77E-01	5.43E-01	4.50E-01	2.01E-01
S2	5.06E-01	3.97E-01	4.82E-01	4.84E-01	5.76E-01	6.14E-01	6.08E-01	3.77E-01	6.18E-01
S3	4.55E-01	2.91E-01	6.21E-01	5.42E-01	4.53E-01	5.19E-01	6.25E-01	4.51E-01	5.63E-01
S4	4.86E-01	3.17E-01	6.08E-01	5.11E-01	4.93E-01	5.41E-01	5.98E-01	4.97E-01	5.79E-01
S5	5.74E-01	5.56E-01	7.45E-01	4.76E-01	5.21E-01	4.59E-01	6.27E-01	4.64E-01	5.37E-01
S6	5.35E-01	5.63E-01	5.13E-01	4.85E-01	4.54E-01	5.27E-01	5.39E-01	4.17E-01	6.19E-01
S7	4.54E-01	3.80E-01	5.23E-01	4.25E-01	5.12E-01	4.50E-01	5.41E-01	4.31E-01	4.70E-01
S8	4.20E-01	4.52E-01	4.76E-01	4.06E-01	4.00E-01	4.80E-01	5.05E-01	5.23E-01	4.68E-01
S9	2.19E-01	5.27E-01	4.20E-01	4.11E-01	5.03E-01	5.31E-01	6.19E-01	4.85E-01	5.13E-01
Mean	**4.48E-01**	**4.18E-01**	**5.45E-01**	**4.71E-01**	**4.66E-01**	**5.11E-01**	**5.78E-01**	**4.55E-01**	**5.08E-01**
SD	**1.03E-01**	**1.12E-01**	**9.78E-02**	**4.70E-02**	**8.55E-02**	**5.09E-02**	**4.63E-02**	**4.41E-02**	**1.28E-01**

Manipulation Stage

The manipulation phase had clearer patterns across tasks for most subjects, with the grasping pattern formed and participants carrying out the task. Figures 4.24 and 4.25 show the jerk and speed metric means and standard deviations across tasks. A clear pattern of higher jerkiness and lower normalized speed for precision grip tasks can be observed when compared with spherical and cylinder grip tasks. Statistically significant difference was found between the changes in smoothness of precision, and cylinder grip tasks ($p < 0.005$ for both jerk and speed metric), and precision and spherical tasks ($p < 0.001$ for both jerk and speed metrics). The buttoning task had the lowest levels of smoothness while dexterity tests were performed with consistently smoother movements across participants.

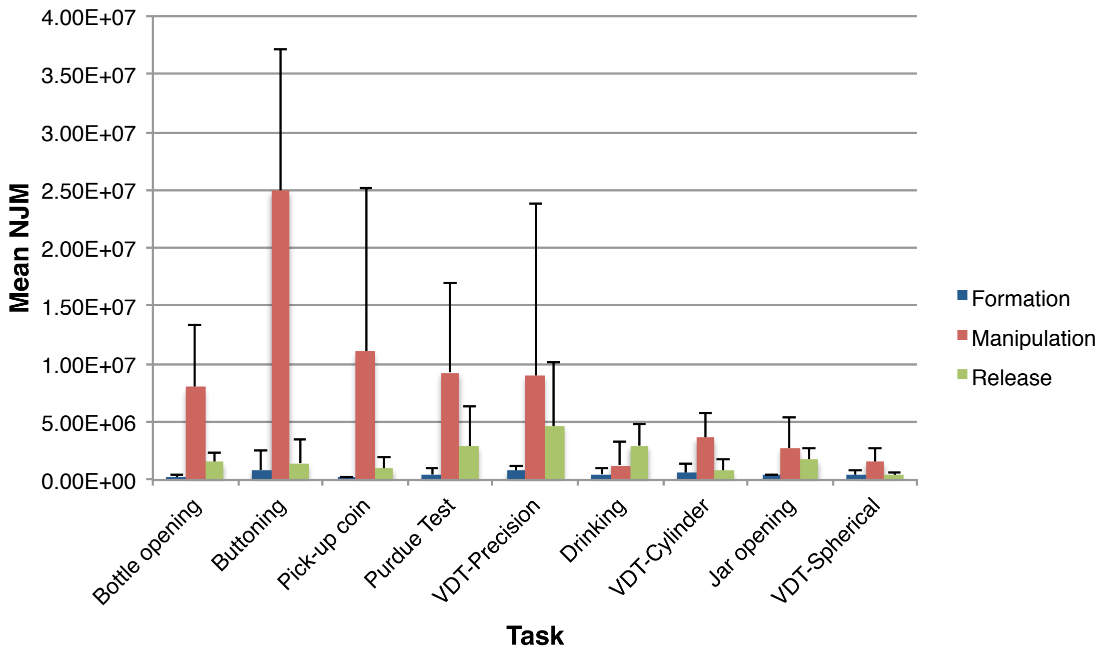


FIGURE 4.24 MEAN NORMALIZED JERK METRIC ACROSS STAGES FOR ALL TASKS

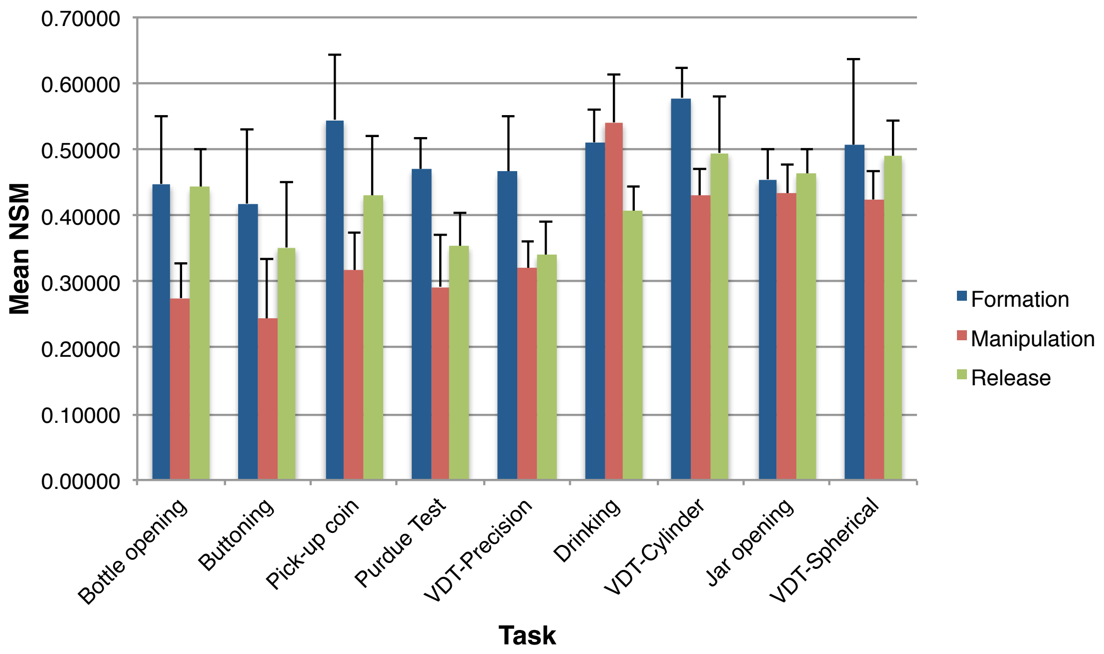


FIGURE 4.25 MEAN NORMALIZED SPEED METRIC ACROSS STAGES FOR ALL TASKS

A second analysis was performed to measure the significance of the difference in smoothness levels between tasks stages. The differences between formation and manipulation values of NJM are plotted in Figure 4.26. Statistical significance ($p < 0.05$) is shown in Table 4.15, with means and standard deviations for the manipulation phase shown in Table 4.16. Subjects' NJM increased significantly in most tasks from formation to manipulation, with significant increases in all tasks except for the drinking task and the VDT-Precision.

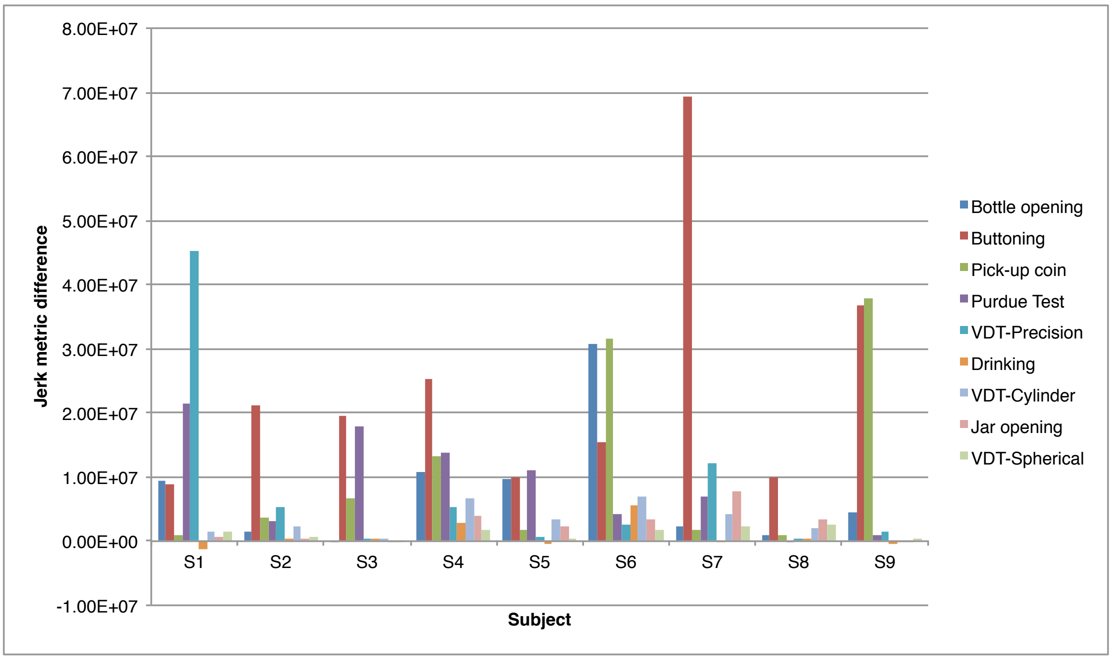


FIGURE 4.26 CHANGES IN JERK METRIC BETWEEN FORMATION AND MANIPULATION STAGES FOR ALL SUBJECTS ACROSS TASKS.

TABLE 4.15 STATISTICAL SIGNIFICANCE (*P* VALUE) OF THE DIFFERENCE BETWEEN THE CHANGES IN JERK METRIC BETWEEN FORMATION AND MANIPULATION STAGES.

Tasks	p values (Significance at p < 0.05)
Bottle opening	0.0296
Buttoning	0.0310
Pick up coin	0.0184
Purdue Test	0.0082
VDT-P	0.0533
Drinking	0.1090
VDT-C	0.0093
Jar opening	0.0204
VDT-S	0.0045

TABLE 4.16 NORMALIZED JERK METRICS ACROSS SUBJECTS AND TASKS. MANIPULATION STAGE

	Bottle opening	Buttoning	Pick-up coin	Purdue Test	VDT-Precision	Drinking	VDT-Cylinder	Jar opening	VDT-Spherical
S1	9.78E+06	1.43E+07	9.85E+05	2.17E+07	4.72E+07	3.61E+05	3.39E+06	1.06E+06	2.04E+06
S2	1.55E+06	2.14E+07	3.90E+06	3.57E+06	6.44E+06	9.37E+05	2.39E+06	8.72E+05	8.46E+05
S3	3.34E+05	1.97E+07	6.95E+06	1.80E+07	8.69E+05	4.53E+05	2.35E+05	4.54E+05	1.34E+05
S4	1.10E+07	2.55E+07	1.32E+07	1.42E+07	5.68E+06	2.97E+06	6.79E+06	3.99E+06	1.94E+06
S5	9.76E+06	1.02E+07	2.10E+06	1.28E+07	1.03E+06	2.23E+05	3.64E+06	2.61E+06	5.25E+05
S6	3.08E+07	1.55E+07	3.17E+07	4.28E+06	2.79E+06	5.87E+06	7.14E+06	3.82E+06	1.73E+06
S7	2.48E+06	6.99E+07	2.00E+06	7.27E+06	1.33E+07	2.76E+05	4.53E+06	8.28E+06	3.72E+06
S8	1.23E+06	1.06E+07	1.18E+06	3.41E+05	1.14E+06	4.40E+05	2.28E+06	3.62E+06	2.82E+06
S9	4.82E+06	3.72E+07	3.82E+07	1.39E+06	2.18E+06	1.26E+05	2.04E+06	1.05E+05	4.30E+05
Mean	**7.97E+06**	**2.49E+07**	**1.11E+07**	**9.28E+06**	**8.96E+06**	**1.29E+06**	**3.60E+06**	**2.76E+06**	**1.58E+06**
SD	**9.49E+06**	**1.88E+07**	**1.41E+07**	**7.66E+06**	**1.49E+07**	**1.93E+06**	**2.25E+06**	**2.57E+06**	**1.20E+06**

Similarly, subjects' smoothness as measured by NSM tended to decrease from formation to manipulation stages (Figure 4.27, Table 4.17), with the changes being significantly large in all but three tasks (drinking, jar opening, VDT-Spherical) (Table 4.18). This similarity between speed and jerk metrics follows from the fact that both measured are normalized for task duration and peak speed. Most subjects showed a significant decrease in smoothness from both metrics across tasks. The amount of decrease in smoothness varied between subjects and tasks, with the buttoning task resulting in the largest differences across subjects.

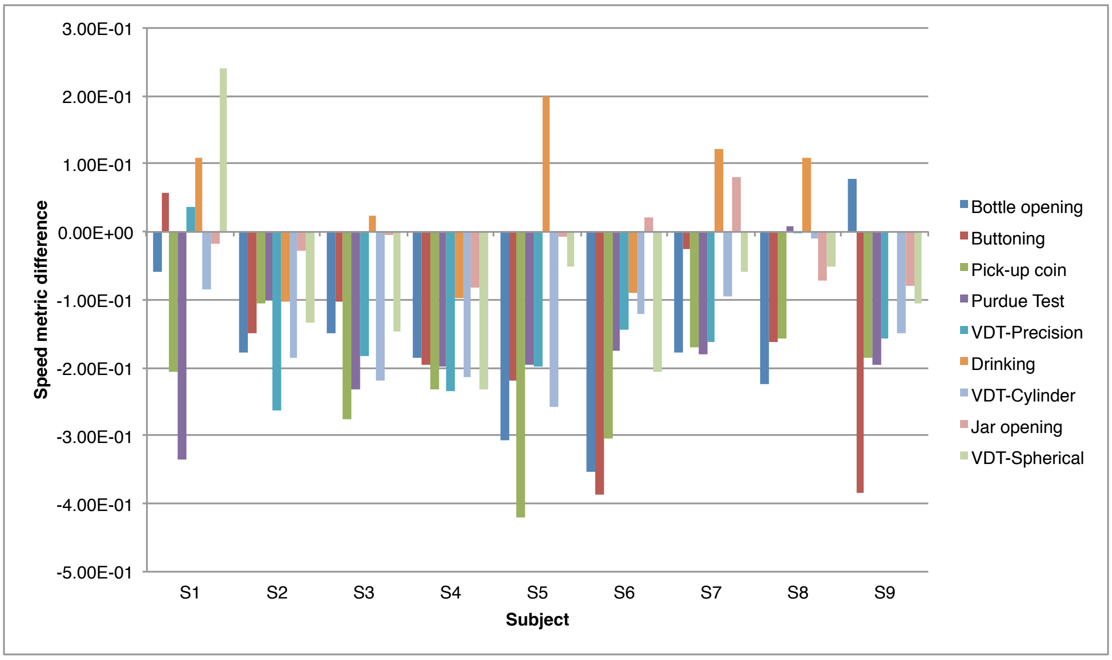


FIGURE 4.27 CHANGES IN SPEED METRIC BETWEEN FORMATION AND MANIPULATION STAGES FOR ALL SUBJECTS ACROSS TASKS.

TABLE 4.17 NORMALIZED SPEED METRICS ACROSS SUBJECTS AND TASKS

	Bottle opening	Buttoning	Pick-up coin	Purdue Test	VDT-Precision	Drinking	VDT-Cylinder	Jar opening	VDT-Spherical
S1	3.27E-01	3.38E-01	3.13E-01	1.63E-01	3.17E-01	5.86E-01	4.57E-01	4.32E-01	4.41E-01
S2	3.28E-01	2.49E-01	3.76E-01	3.83E-01	3.13E-01	5.12E-01	4.22E-01	3.49E-01	4.83E-01
S3	3.05E-01	1.87E-01	3.45E-01	3.11E-01	2.70E-01	5.43E-01	4.06E-01	4.46E-01	4.15E-01
S4	3.02E-01	1.22E-01	3.76E-01	3.12E-01	2.60E-01	4.43E-01	3.85E-01	4.16E-01	3.47E-01
S5	2.66E-01	3.38E-01	3.25E-01	2.80E-01	3.23E-01	6.58E-01	3.70E-01	4.56E-01	4.85E-01
S6	1.82E-01	1.77E-01	2.11E-01	3.10E-01	3.11E-01	4.36E-01	4.18E-01	4.38E-01	4.13E-01
S7	2.76E-01	3.55E-01	3.53E-01	2.45E-01	3.49E-01	5.72E-01	4.47E-01	5.12E-01	4.11E-01
S8	1.96E-01	2.89E-01	3.18E-01	4.13E-01	3.97E-01	5.89E-01	4.95E-01	4.51E-01	4.17E-01
S9	2.96E-01	1.42E-01	2.35E-01	2.15E-01	3.47E-01	5.31E-01	4.71E-01	4.05E-01	4.08E-01
Mean	**2.75E-01**	**2.44E-01**	**3.17E-01**	**2.93E-01**	**3.21E-01**	**5.41E-01**	**4.30E-01**	**4.34E-01**	**4.25E-01**
SD	**5.31E-02**	**9.01E-02**	**5.83E-02**	**7.83E-02**	**4.14E-02**	**7.12E-02**	**4.08E-02**	**4.37E-02**	**4.19E-02**

TABLE 4.18 STATISTICAL SIGNIFICANCE (*P* VALUE) OF THE DIFFERENCE BETWEEN THE CHANGES IN SPEED METRIC BETWEEN FORMATION AND MANIPULATION STAGES.

Tasks	p values (Significance at p < 0.05)
Bottle opening	0.0017
Buttoning	0.0081
Pick up coin	< 0.001
Purdue Test	< 0.0001
VDT-P	0.0056
Drinking	0.7541
VDT-C	< 0.001
Jar opening	0.1052
VDT-S	0.0613

Release Stage

Tables 4.19 and 4.20 show the jerk and speed metrics values for all subjects across tasks during the release stage. Clear patterns of smoothness between grip styles and tasks are no longer observable as participants release the object extending the fingers and move the hand back to the starting position with similarly smooth trajectories (Figures 4.24, 4.25). NJM values were below 7×10^6 for most tasks and subjects and precision dexterity tests having the largest jerk values (above 1.2×10^7).

TABLE 4.19 NORMALIZED JERK METRICS ACROSS SUBJECTS AND TASKS. MANIPULATION STAGE

	Bottle opening	Buttoning	Pick-up coin	Purdue Test	VDT-Precision	Drinking	VDT-Cylinder	Jar opening	VDT-Spherical
S1	1.50E+06	6.57E+06	4.41E+05	1.73E+06	3.00E+06	1.77E+06	3.25E+06	2.65E+06	3.43E+05
S2	1.25E+06	1.01E+06	3.24E+05	1.04E+06	1.79E+07	5.91E+06	9.91E+04	2.17E+06	1.55E+05
S3	1.91E+06	3.03E+05	6.04E+05	1.00E+06	2.77E+06	2.86E+06	5.62E+05	1.62E+06	5.73E+05
S4	1.03E+06	2.76E+05	2.39E+06	1.63E+06	8.08E+05	4.81E+05	1.25E+06	9.16E+05	8.80E+05
S5	8.39E+05	1.52E+06	3.74E+05	1.18E+07	4.40E+06	3.72E+06	6.28E+05	2.50E+06	3.71E+05
S6	7.07E+05	4.14E+05	2.28E+05	7.09E+05	1.25E+06	6.72E+05	2.40E+05	2.89E+06	8.69E+04
S7	3.21E+06	8.61E+05	6.31E+05	2.28E+06	7.78E+06	2.45E+06	4.86E+05	2.66E+06	1.98E+05
S8	1.86E+06	6.90E+05	5.74E+05	2.85E+06	2.35E+06	3.04E+06	4.63E+05	4.64E+05	2.84E+05
S9	1.33E+06	1.40E+06	3.19E+06	3.16E+06	1.62E+06	5.72E+06	2.27E+05	3.59E+05	5.94E+05
Mean	**1.51E+06**	**1.45E+06**	**9.73E+05**	**2.91E+06**	**4.66E+06**	**2.96E+06**	**8.00E+05**	**1.80E+06**	**3.87E+05**
SD	**7.58E+05**	**1.97E+06**	**1.06E+06**	**3.44E+06**	**5.41E+06**	**1.93E+06**	**9.77E+05**	**9.97E+05**	**2.53E+05**

TABLE 4.20 NORMALIZED SPEED METRICS ACROSS SUBJECTS AND TASKS. MANIPULATION STAGE

	Bottle opening	Buttoning	Pick-up coin	Purdue Test	VDT-Precision	Drinking	VDT-Cylinder	Jar opening	VDT-Spherical
S1	4.06E-01	2.54E-01	4.16E-01	2.73E-01	3.29E-01	3.87E-01	4.33E-01	4.64E-01	4.76E-01
S2	4.34E-01	4.09E-01	5.27E-01	3.98E-01	3.92E-01	4.13E-01	5.53E-01	4.59E-01	5.11E-01
S3	5.24E-01	2.50E-01	4.73E-01	4.27E-01	3.50E-01	3.61E-01	5.71E-01	4.69E-01	4.28E-01
S4	4.12E-01	4.96E-01	2.79E-01	3.74E-01	4.01E-01	3.58E-01	3.06E-01	5.16E-01	4.11E-01
S5	5.37E-01	4.44E-01	5.46E-01	3.87E-01	2.83E-01	4.20E-01	5.58E-01	4.07E-01	4.86E-01
S6	4.83E-01	2.74E-01	4.26E-01	3.62E-01	3.90E-01	4.26E-01	4.41E-01	4.41E-01	4.74E-01
S7	3.89E-01	4.11E-01	4.47E-01	3.45E-01	2.74E-01	4.64E-01	5.39E-01	4.17E-01	5.44E-01
S8	4.14E-01	3.90E-01	4.64E-01	3.06E-01	3.52E-01	3.80E-01	5.15E-01	4.83E-01	4.88E-01
S9	3.84E-01	2.38E-01	2.97E-01	3.14E-01	2.87E-01	4.52E-01	5.39E-01	5.13E-01	5.93E-01
Mean	**4.43E-01**	**3.52E-01**	**4.31E-01**	**3.54E-01**	**3.40E-01**	**4.07E-01**	**4.95E-01**	**4.63E-01**	**4.90E-01**
SD	**5.77E-02**	**9.77E-02**	**9.13E-02**	**4.92E-02**	**4.96E-02**	**3.78E-02**	**8.64E-02**	**3.78E-02**	**5.55E-02**

NSM values were between 0.2 and 0.6 across tasks and subjects with precision tasks having the lowest smoothness levels (0.22 for the buttoning task, 0.28 for the Purdue Test, 0.3 for the pick-up coin task), although this difference was not found to be statistically significant.

The differences between manipulation and release stages values of jerk and speed metrics are plotted in Figures 4.28 and 4.29. Statistical significance (p values) of the changes is shown in Tables 4.21 and 4.22.

Most subjects showed a significant increase in smoothness, with lower NJM values and larger NSM showing an improved smoother finger movement once the manipulative stage of tasks was finished and participants extended the fingers and relaxed the hand. The amount of change in smoothness metrics varied between subjects and tasks, with lager NJM changes for the buttoning task (maximum decrease of 6.8 x 10^7) and larger increase of NSM during bottle opening and buttoning tasks.

Observed changes in NJM were significant ($p < 0.05$) for all but 4 tasks (VDT-Precision, drinking, and jar opening), while changes of NSM were not statistically significant for the VDT-Cylinder, jar opening, and VDT-Precision.

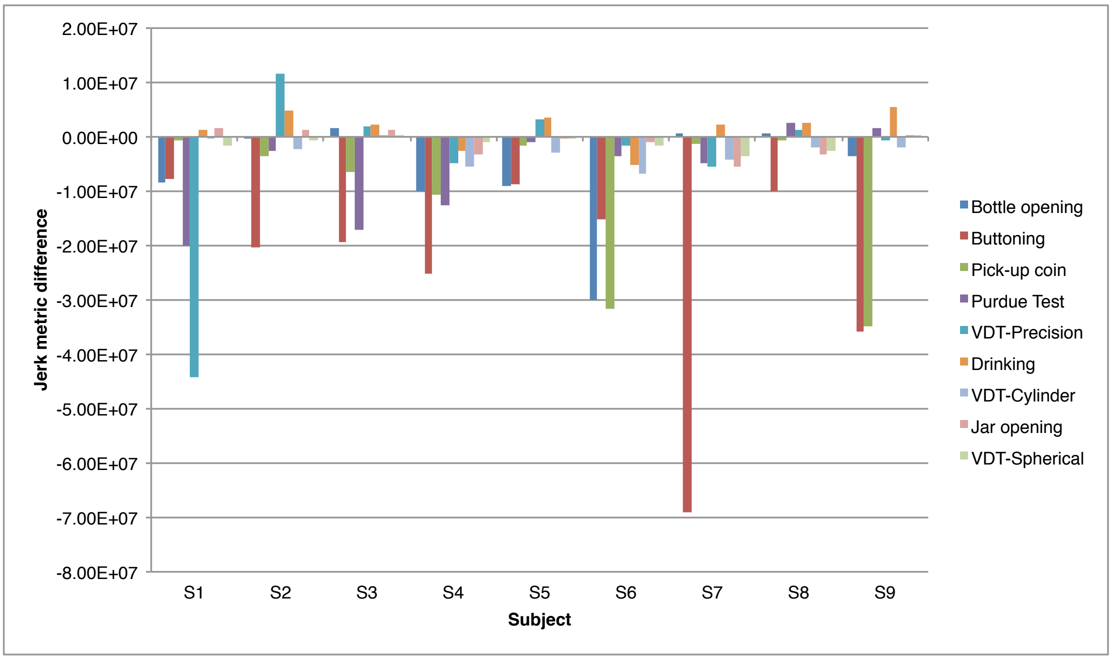


FIGURE 4.28 CHANGES IN JERK METRIC BETWEEN MANIPULATION AND RELEASE STAGES FOR ALL SUBJECTS ACROSS TASKS.

TABLE 4.21 STATISTICAL SIGNIFICANCE (*P* VALUE) OF THE DIFFERENCE BETWEEN THE CHANGES IN JERK METRIC BETWEEN FORMATION AND MANIPULATION STAGES.

Tasks	p values (Significance at $p < 0.05$)
Bottle opening	0.0605
Buttoning	0.0085
Pick up coin	0.0123
Purdue Test	0.0105
VDT-P	0.1407
Drinking	0.6826
VDT-C	0.0063
Jar opening	0.2593
VDT-S	0.0068

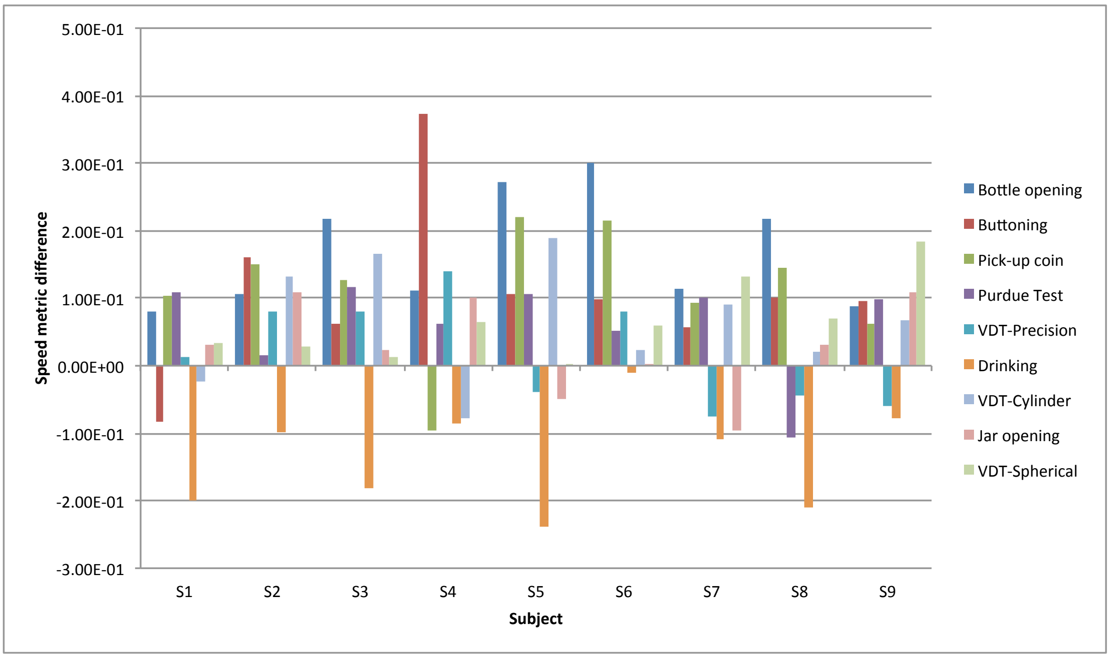


FIGURE 4.29 CHANGES IN SPEED METRIC BETWEEN MANIPULATION AND RELEASE STAGES FOR ALL SUBJECTS ACROSS TASKS.

TABLE 4.22 STATISTICAL SIGNIFICANCE (*P* VALUE) OF THE DIFFERENCE BETWEEN THE CHANGES IN SPEED METRIC BETWEEN FORMATION AND MANIPULATION STAGES.

Tasks	p values (Significance at $p < 0.05$)
Bottle opening	< 0.001
Buttoning	0.0092
Pick up coin	0.0151
Purdue Test	0.0062
VDT-P	0.3093
Drinking	0.0010
VDT-C	0.1453
Jar opening	0.5414
VDT-S	0.0361

4.5.4 Summary and Discussion

This experimental study was aimed at examining finger trajectory characteristics during manipulative tasks and their relation with movement patterns across activities of daily living and dexterity tests. In this study, previously developed measures of trajectory smoothness - normalized jerk [155] and normalized speed [42]- were computed for the three pre-defined stages of manipulative tasks (formation, manipulation and release) and the results were then compared across subjects and grip styles.

Previous works on human movement trajectory analysis have shown the validity and efficiency of dimensionless jerk measures when used to measure movement smoothness, allowing the analysis to avoid the effects of movement amplitude and task duration [30], [36], [42], [155]. Normalized speed metric was originally developed to account for the sequence of sub-movements underlying continuous movements, and their effects on movement smoothness.

Nevertheless, a study employing these smoothness metrics to analyse finger trajectories during daily living manipulative tasks and the relations between trajectory and grasping patterns had yet to be made.

Formation Stage

Results from the formation stage showed no particular pattern across subjects and tasks, with smooth movements characterised by jerk values below 1×10^6 and speed metric values between 0.2 and 0.7. These values, along with the fact that there was no significant difference across tasks and grip styles may suggest finger movement smoothness is not greatly affected during the formation stage in healthy individuals. Previous works analysing hand trajectory during reaching tasks have shown that smoothness is a characteristic of unimpaired movements, with early movements made by patients recovering from stroke characterised by a series of discrete sub-movements and lack of smoothness [156]. Results from the formation (reaching) stage are in line with such findings, with participants employing similar approaching strategies and no evident difference in smoothness between grip styles.

Manipulation Stage

During the manipulation stage smoother movements for cylinder and spherical grip tasks were observed across participants when compared against precision grip tasks, with higher NJM and lower NSM for precision grip tasks. These observed differences were proved to be statistically significant via paired t-test at the 5% significance level for all subjects ($p < 0.005$ for differences between precision and cylinder tasks, and $p < 0.001$ for differences between precision and spherical grip tasks), and precision and spherical tasks ($p < 0.001$ for both jerk and speed metrics). Differences during the manipulation stage across grip styles suggest finer dexterous tasks are made of less-smooth movements when compared to tasks requiring the manipulation of larger objects. Moreover, mean values of NJM were higher for precision daily living tasks when compared against dexterity tests, with the buttoning task averaging 2.65×10^7 across subjects. The lack of smoothness during precision tasks may suggest struggle to control and manipulate smaller objects, resulting in movements composed of sudden changes in acceleration.

In addition, the manipulation stage was characterised by decreased smoothness across tasks and subjects in both jerk and speed metrics. The statistical significance of the observed differences in smoothness levels between stages was analysed through two-sample t-test ($p < 0.05$). Increases of jerkiness were statistically significant in all tasks except for the drinking task and the VDT-Precision. Speed metric decreases were shown to be statistically significant in all but three tasks (drinking, jar opening, VDT-Spherical). These changes in smoothness between tasks stages indicate an increase in the number of sub-movements and sudden stops during the manipulation of objects when compared to the formation of the grasping pattern and reaching for the object. This observed pattern renders additional evidence that, although some jerk-based measures of smoothness have been shown to be insensitive to sudden stops and periods of arrest, the dimensionless squared jerk measure used for this analysis increases with the temporal separation of sub-movements, thus, properly reflecting the change of movement shape.

Release Stage

During the release stage there were no clear movement smoothness patterns across tasks and grip styles with NJM values below 7×10^6 and NSM values between 0.2 and 0.6 across tasks and subjects. Tasks requiring a precision grip had the lowest smoothness levels as measured by both jerk and speed metrics, although this difference was not found to be statistically significant. Findings from this stage are in line with results from the formation stage as well as previous works regarding arm movement and reaching; suggesting smooth, un-interrupted finger movements as the hand extended and went back to the starting position.

Overall, tasks were smoother across subjects during the released stage when compared against the manipulation phase, with NJM values significantly smaller for all but 4 tasks and NSM changes statistically significant for all but 3 tasks ($p < 0.05$). The buttoning task produced the lower levels of smoothness from jerk and speed metrics, suggesting more periods of arrest and irregular movement shape as participants released the last button and extended the fingers to a relaxed posture.

In conclusion the high resolution and specificity of trajectory smoothness measures may allow the observation of other previously unobservable factors that account for dexterity. The use of these measures to complement other kinematic variables such as synergies and range of motion would help to develop a more robust understanding of human movement, and, particularly, dexterous movements. Results from this study extend previous works on trajectory analysis and movement smoothness [30], [32], [39], [138] by showing clear decreases in smoothness during the manipulation phase of tasks, as well as significant differences in quality of trajectory between the three most commonly used grasping patterns. Furthermore, the lower smoothness values obtained from precision grip tasks when compared against cylinder and spherical grips are in line with results from the rest of the analyses conducted as part of this research, providing additional evidence to the role of grip choice and grasping strategies in manipulative tasks. In particular, lower smoothness during the manipulation phase of precision tasks may be due to the amount of independent finger movement previously observed in both the correlation and principal components analyses, further evidencing the role of fingers that are not necessarily in contact with the object. Moreover, it was shown that movement characteristics related to object size and grasping pattern choice may be quantified through measurement of smoothness, suggesting there is a potential use of this technique to further understand grasping strategies and development of manipulative skills. A follow-up study on a larger sample may provide validity and reliability information of this approach, as well as normative data on quality of movement across levels of skill and hand function.

Chapter 5

General Discussion

The main goals of this research were to understand dexterity and to develop accurate and efficient methods to assess hand function as one of the underlying factors of dexterity. Based on previous work on the subject, dexterity was defined for this research as *the ability to adequately solve an emerging motor problem accurately, quickly, rationally, and resourcefully,* accordingly, a robust and precise dexterity assessment method must take into consideration hand movement characteristics and the motor control patterns that activate and coordinate such movements. The experimental studies conducted as part of this research involved quantitative examination and in-depth analysis of kinematic and movement coordination data, focused on movements performed during standard activities of daily living (ADL) and traditional timed dexterity tests in a lab environment.

The initial finding from this work is that dexterity must not be understood as a skill or a combination of skills, but as a psychophysiological phenomenon that defines the relationship between the nervous system and the performance of precise movements.

Furthermore, although dexterity is typically assessed by tests measuring the time taken to perform a number of repetitions of the precision grip, a thorough evaluation of dexterity and hand function must take into consideration the wide range of movements and prehensile patterns performed by the hand in daily tasks, and it must incorporate objective analyses of such patterns. Therefore, this research made an effort to characterise the grasping patterns that accurately represent a range of postures commonly used during daily living hand-object interactions, as these interactions have the greater influence in independent living, quality of life, and overall functionality.

Conclusions from the literature review section of this work led to the selection of a set of representative activities of daily living based on the most frequently used grip styles, and the Purdue Pegboard Test was used as a gold standard dexterity test to compare quantitative characteristics of hand and finger movement. In addition, the Variable Dexterity Test was designed and built as an alternative, flexible, and cost-effective dexterity test that could involve the selected range of grip styles during the experimental studies of this research.

The above-mentioned definition of dexterity and the understanding of existing limitations in hand function assessments led to the design of a series of experimental studies in order to achieve the main goal of developing an efficient and accurate assessment of dexterity.

Three stages of manipulative tasks were defined for the experimental studies: formation of the grip, manipulation, and release; in order to increase accuracy and aid in the identification of patterns across the range of grip styles. Moreover, the definition of stages, phases, or behavioural epochs that constitute manipulative tasks has been used in previous work [24], [157], and it has been shown that prehension tasks have clear differences between reach and grasp phases on the conceptual levels of motor control and neural processing [74], [75].

Moreover, previous efforts to understand reaching and grasping have produced fundamental findings on learning and skill acquisition. This research aimed to test the viability of a number of acquisition and analysis techniques that could aid in further developing these findings. The experimental studies of this research were designed to build on the functional differentiation between phases, aiming to acquire high quality data on a larger range of movements and tasks.

The data acquisition protocol was developed based on previous efforts [20], [21], [117], [122] to adapt the complex process of motion capture for hand movement analysis, aiming to allowing the measurement of all the required degrees of freedom of the hand while at the same time reducing the number of markers and the level of marker interference with normal hand use. In one of such previous efforts, Sancho-Bru [20] used 29 reflective markers on a similar marker topology to the one used for this research, reporting a global error of 6.68° and relatively small errors in repeatability and reproducibility (3.43° and 4.23°, respectively). Furthermore, the method accuracy was calculated by comparing results with data from electronic goniometers, showing no statistically significant difference and high correlation between both techniques.

Moreover, the configurations of the markers found in these studies proved to be repeatable between raters, demonstrating the protocols can be applied in clinical research studies [122]

The use of a simplified kinematic measuring technique has been found to be a reasonable approximation, although by adjusting marker topologies and the computation of kinematic variables, these techniques incur in potential sources of errors such as skin movement or correct definition of joint centres. This research aimed to build on these simplified acquisition techniques testing the viability to obtain and analyse kinematic data during the performance of both ADLs and dexterity tests.

The three experimental studies consisted of the analysis of hand and finger kinematics, looking to identify movement patterns that characterise manipulative tasks across the pre-defined stages and grip styles.

In the first study, finger movement correlation patterns across tasks' stages suggested a relation between object size, grip style, and finger interdependencies. In particular, tasks requiring finer movements were found to be characterised by low cross-correlation, indicating a higher level of independent finger movement. Furthermore, tasks requiring grosser movements (cylinder and spherical grip styles) consistently resulted in higher cross-correlation coefficients across movements of digits 2-4, indicating manipulation of larger objects generally require higher degree of interdependent finger flexion/extension when compared to precision tasks.

Results from the analysis of finger movement correlation rendered evidence of the wide range of dexterity levels that are associated with the performance of different grasping patterns, and further stressed the need for assessment procedures and quantitative methods that take into consideration grosser finger movements. In addition, cross-correlation coefficients from participants performing the VDT sub-tests were comparable to those from related activities of daily living across grip styles, further suggesting the suitability of the VDT as a test of manipulative task performance.

Moreover, the use of finger movement cross-correlation provided fundamental evidence of the behaviour of individual degrees of freedom across the hand, and the relationships between them. Additionally, results from this study revealed clear differences between movement patterns across tasks' stages, with the formation and release phases resulting in a larger set of variable correlation patterns across tasks, while there were clearer patterns among grasping patterns during the manipulation stage.

Previous works on finger movement patterns have provided results in line with findings from this study, showing the existence of movement patterns and simultaneous movements of joints for specific tasks. Anatomical and neural factors produce correlated joint movements (named as kinematic synergies in most works), in what can be defined as independent mechanical DoFs [26].

The second experimental study conducted as part of this research aimed at finding additional evidence of the existence of kinematic synergies, and their relation with the performance of a range of manipulative tasks and dexterous finger movements through principal component analysis. Furthermore, the study was conducted looking to validate findings from the cross-correlation analysis, as well as to build on previous conclusions from works employing principal component analysis for the examination of hand movement [12], [24], [125].

Results from the PCA study provided additional evidence that combinations of a small number of kinematic synergies allow for the reconstruction of an entire set of kinematic variables. Additionally, it aimed to fill a gap within this type of studies, looking into the role of kinematic synergies during daily living tasks and their relation with synergies found in traditional dexterity tests.

Analysis of the three pre-defined phases of the tasks produced clear identifiable synergistic movement patterns in line with results from the cross-correlation study, with the formation and release stages characterised by kinematic synergies having greater variability, and percentage of variation not strictly dependent on grip style or task.

During the manipulation phase, however, the identified kinematic patterns are clearer among tasks, with movement variations tending to be smaller during grosser grasping patterns (cylinder and spherical) when compared to finer movements. These results further suggest a lower degree of finger movement interdependence during manipulation of smaller objects, with fingers having individualised, dexterous movements.

In the third kinematic study, performance of the battery of ADLs and dexterity tests was analysed through the three-dimensional trajectory of finger movements, aiming at evaluating the reliability of previously developed smoothness metrics as measures of hand function and dexterity, as well as comparing trajectory smoothness between dexterity tests and activities of daily living. The principles behind this study stem from previous efforts utilising quality of trajectory, measured as movement smoothness, as a kinematic variable indicative of motor performance of both healthy subjects and persons with motor control and musculoskeletal impairments [30]–[32], [42].

Some of these previous works have been focused on patients recovering from stroke and other motor related impairments, and have shown a reduction in trajectory smoothness and segmentation of continuous movements [34], [42] when compared against healthy individuals. In this experimental study, movements of healthy subjects were analysed, aiming to identify evidence of discrete sub-movements in the selection of grip styles and tasks.

One challenge faced by the majority of works on the subject has been the mixture of results from different studies using jerk metrics, each of which producing different results with changes in movement amplitude, duration and intervals of arrest. This is an important consideration as movements made during dexterous manipulative tasks are often slower than those of simpler tasks [42], [155], [156]. Consequently, as a second objective, this study aimed to produce additional evidence to support conclusions from studies that have shown that dimensionless jerk metrics accurately reflect skilled, coordinated movement. changes of movement shape, independent of amplitude and duration, truly reflecting common sources of lack of smoothness such as speed peaks or periods of arrest.

In addition to dimensionless jerk, normalized mean speed [42] was calculated from finger kinematic data, with participants performing the selected battery of activities of daily living and dexterity tests. The high resolution and specificity of trajectory smoothness measures allowed for the observation of other previously unobservable factors that account for dexterous movements in all three phases of manipulative tasks.

Moreover, results from this study further assert conclusions from the first two kinematic studies in this research, while at the same time expanding on previous works on trajectory analysis and movement smoothness by showing clear decreases in smoothness during the manipulation phase of tasks and statistically significant differences in smoothness between grasping patterns. These observed differences confirm the role of object size, nature of the task, and grasping pattern choice in the dexterous performance of tasks. Results are also in line with studies of development and recovery that suggest that smoothness is a result of learned coordination [42], [158], as movements were shown to become more smooth as tasks' motor control and dexterity requirements decrease.

The identified patterns found in this study show that a dimensionless jerk measure may be used to effectively reflect changes of movement shape, independent of amplitude and duration, while still reflective of common changes of smoothness associated with multiple speed peaks and sudden stops in manipulative tasks.

In addition, the use of smoothness measures to complement other kinematic variables such as movement cross-correlation, range of motion, and identification of synergies proved to have the potential to aid in the development of a more robust assessment of hand function, and, particularly, the kinematic aspects associated with dexterity.

The assessment and understanding of the hand function parameters analysed in this research were proved to be consistent with a broader definition of dexterity, taking into consideration not only time to perform a specific movement pattern, but also the relationship between individual and interdependent finger movements, kinematic synergies, trajectory smoothness, and the range of manipulative strategies involved in commonly used grasping patterns.

A comparative look at the connection between outcomes of different analysis methods and the differences between grasping patterns and tasks phases led to new insights in the assessment of manipulative tasks. First, the congruency between cross-correlation patterns, principal components, and finger trajectory suggests that kinematic synergies and interdependent movement are greater in grosser grips tasks, with fingers flexing and extending synchronously to form the grasping pattern, manipulate the object, and dissolve the grip. Secondly, the potential use of these techniques to provide insight into reaching, grasping, and releasing skills acquisition, through the use of both traditional ADLs and abstract tasks. Third, the specificity of analysing individual tasks' stages proved to help in the recognition of some of the different approaches to grasping, particularly during the manipulation phase, with the quantification of the role of individual fingers helping in our understanding of grasping patterns and grasping classifications.

These insights provoke interesting questions such as whether two comparable kinematic patterns from different movements can be considered as equivalent and how to accurately define movement complexity when assessing quality of hand function.

Such interpretations also indicate a robust relationship between the sensory and the development of a variety of skilful movement patterns. With the level of dexterity defining how quickly and successfully a person can develop a certain motor skill and what level of proficiency can be achieved.

Chapter 6

Conclusions and Recommendations

This research was aimed at the development accurate and efficient methods to assess hand function as one of the fundamental features of dexterity. Through literature review, exploratory studies, and project planning, a series of experimental studies were designed to understand and quantitatively examine the kinematic and movement coordination aspects of such a complex phenomenon. The study was focused on movements required for instrumental activities of daily living (ADL) and traditional dexterity tests, with a secondary goal being the evaluation of such tests as standard methods to assess hand functionality.

The designed methods and analysis techniques provided fundamental insights into our understanding of the relationships between motor coordination, movement, and hand function. More importantly, the data and conclusions derived from this research have the potential to aid in the development of improved health care practice, assistive technologies, and quality of life research, by providing practitioners and researchers with updated knowledge on human movement analysis, hand function, and dexterity.

The following specific conclusions can be drawn from this research work:

i) Although dexterity has been understood as a skill or a combination of skills, results from this study indicate it should be defined as a complex psychophysiological phenomenon that defines the relationship between the nervous system and the performance of movements to solve motor problems.

ii) It was shown how existing dexterity tests and apparatus used by occupational therapists and orthopaedics can not accurately capture the total array of features and characteristics that account for proficient performance of hand tasks. In particular, proficient performance of the precision grip is not a conclusive indicative of high dexterity, and a wide range of moving patterns and postures have to be included in any assessment of hand function and dexterity. The proposed Variable Dexterity Test and the range of acquisition methods and analyses proposed in this work proved to be robust approaches that precisely match the complex series of parameters that account for dexterous movements.

iii) The Variable Dexterity Test construction standards and design make the apparatus a cost-effective, easy to administer solution to the problem of assessing a wider range of grasping patterns through timed performance.

iv) Analysis of finger movement cross-correlation provided fundamental evidence of the behaviour of individual degrees of freedom across the hand, and the relationships between them. Specifically, smaller objects and finer grasping patterns produced uncorrelated finger movements when compared against grosser tasks. Thus, it can be concluded that finer movements are made of fingers flexing and extending rapidly and independently.

v) Principal components analysis allowed for the identification of kinematic synergies that are instrumental in the performance of manipulative tasks. Results further suggested a lower degree of finger movement interdependence during manipulation of smaller objects, when compared with grosser tasks; cylinder and spherical grip are accomplished by interdependent finger movement.

vi) Trajectory smoothness analysis further assert conclusions from the first two kinematic studies by showing clear decreases in smoothness during the precision grip tasks when compared to spherical and cylinder grip tasks. These observed differences confirm the role of object size, nature of the task, and grasping pattern choice in the dexterous performance of tasks. Concretely, grosser movements, and manipulation of larger objects are made of smooth trajectories, indicating lower level of sub-movements segmentation.

The overall conclusion of this research is that the broad range of movements and patterns of the human hand, along with the infinite number of possible coordination strategies result in the need of identification of movement patterns in order to accurately assess dexterity and hand function. Furthermore, although timed tests are time-efficient and cost-effective methods to measure dexterity, a truly objective and robust measurement of dexterity most cover all the factors and parameters that play a role in this phenomenon.

Previous studies on hand function and assessment of dexterity have been mostly focused on the performance of the precision grip (also known as pinch grip, or 3-jaw chuck), with emphasis on the time taken to complete tasks. The in-depth understanding of dexterity and the identification of its fundamental factors in this research provide a robust knowledge base, while a series of methods to accurately and precisely assess such factors having the potential to be included in future normative and validity longitudinal research studies.

Additionally, this study has allowed for the characterisation of different levels of dexterity in a range of grasping patterns and tasks, with finer movements being associated with higher degree of dexterous, complex movements when compared to grosser tasks. These findings, however, also imply that the factors of dexterity needed to proficiently perform a fine task differ significantly from those required to perform grosser tasks, and thus, assessment must take into consideration these differences.

The impact of this research relies on the importance of loss of dexterity as a target for rehabilitation, assistive technologies, robotics, and product design research, and its results suggest opportunities for improvement in our assessment of human movement.

Furthermore, although there are a great number of studies of lower limbs focused that have allowed for the development and validation of a range of metrics and methods to assess stable walking, this study fills a considerable gap in the analysis of upper limbs function, proposing a series of metrics and methods that may prove to be standard upper limb function measures and methods.

Future work will be focused on the limitations of this research. A larger sample size will provide information of the validity and reliability of the analysis techniques, while at the same time allowing a robust study of the accuracy and repeatability of the data acquisition protocols. The motion capture protocol proposed was adjusted to allow the measurement of all the required degrees of freedom of the hand while at the same time reducing the number of markers and the level of marker interference with normal hand use. The effects of this simplified kinematic measuring technique have to be fully reviewed and assessed for the specific analysis methods used in this research.

A number of alternative approaches to the measurement of human movement variability and pattern recognition were not explored (vector coding, factor analysis, dynamic stability methods), and their viability and accuracy has to be assessed and compared with the techniques proposed in this work.

In addition, although the Variable Dexterity Test proved to be a flexible and cost-effective experimental tool, it has yet to be fully developed in order to be reliably used as dexterity assessment method for clinical practice. Further work regarding the VDT should include a thorough analysis of the effects of the rater-timed nature of the score and its limitations providing information on overall functionality. Additionally, it requires a clearer definition of the assessment procedure and standardisation of the protocol. The choice of abstract objects and grasping patterns may be benefited by further validation and reliability studies from larger samples across age spans and hand function conditions.

Due to their complexity and the required equipment, the protocols and methods used in this research are not intended to be transferable to a clinical environment, however, the potential use of the described techniques in clinical research, sports science, and research on skills acquisition make this work an important contribution to the field. Furthermore, this work has built on previous efforts to standardise hand movement analysis, learning from the advantages and limitations of such efforts and testing their viability across a range of tasks.

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Appendix A

University Research Ethics Application Form for Staff and PGRs

This form has been approved by the University Research Ethics Committee (UREC)

Date:	16/04/13
Name of applicant:	Victor Gonzalez-Sanchez
Research project title:	Design for ease of use. Assessing dexterity in activities of daily living (ADL).

Appendix B

International Journal of Therapy and Rehabilitation

Development of the Variable Dexterity Test: Construction, reliability and validity

V. González, J. Rowson, A. Yoxall

Abstract

Introduction

This work introduces a dexterity test designed to assess individual types of dexterity utilised whilst carrying out activities of daily living (ADL). Validity and reliability studies for this new test were carried out and the results are shown in this article.

Method

Reliability and validity estimates were obtained from 24 healthy participants. Test-retest and Inter-rater reliability were assessed via ANOVA. The validity of the test was estimated correlating scores from the VDT with the participant's proficiency to complete each of 4 ADL as well as a gold-standard dexterity test

Results/Findings

The test produces consistent results among a pilot group with both a single assessor (test-retest reliability) and multiple assessors (inter-rater reliability). Correlations between VDT scores and proficiency to perform ADL were found to be high for most of the subtests. Correlation between the scores from the Purdue Pegboard Test and the VDT was shown to be high.

Conclusion

The VDT proved to be a flexible, reliable, valid tool that approaches the problem of assessing dexterity focusing on activities of daily living for the pilot group. Validity and reliability estimates show encouraging values, proving that the VDT can be used as an accurate method to assess more than one type of dexterity.

Design 4 Health European Conference, 2013

Motion capture analysis of dexterity tests

V. González, J. Rowson, A. Yoxall

Abstract

A person's ability to manipulate objects is known as their dexterity; it can be broken down in a variety of ways into different subtypes e.g. macro-dexterity, and micro-dexterity. Most people will go through their daily lives unaware of their dexterity level but for those who are recovering from stroke or loss of dexterity there are a wide variety of dexterity tests available to health practitioners to assess that person's ability and need for support. Tests such as the Purdue Pegboard and Moberg Pickup are used to do this assessment, however they do not always test the dexterity subtypes required for activities of daily living (ADL).

This work is to identify the dexterity subtypes assessed by common dexterity tests using video ethnography and motion capture. Parallel to this, using the same methods, five ADL were assessed for the dexterity subtypes required to complete them.

This investigation was based on 8 healthy participants between 24 and 40 years old carrying out a selection of 5 dexterity tests and 5 ADLs, with the main goal being the identification of the biomechanical factors that account for dexterity. Additional assessment was carried out to relate the subtypes of dexterity to the performance levels achieved.

It has been shown that in order to accurately measure hand function it is essential to take into account the dynamics, perception of movement and speed of manipulation as well as the relationship between all these factors and functional tasks. Establishing links between dexterity tests, ADLs and dexterity subtypes will aid health practitioners in their understanding of the assessment results. It will also help in the development of accurate, repeatable and inclusive methods for the measurement of dexterity, truly assessing a person's ability to carry out ADLs and thus their capability to maintain their independence.

Evaluation of finger interdependencies during activities of daily living

V. González, J. Rowson, A. Yoxall

Abstract

Introduction

Dexterity assessment is important in the clinical medicine, inclusive design, and biomechanical fields. However, most movement assessment results require an understanding of biomechanics, mathematics and statistics limiting its applicability within clinical and design practice.

This article reports an experimental study that aimed to quantitatively analyse motion correlation patterns across the fingers, and examine the kinematic synergies during manipulative tasks, producing applicable and accessible data for therapy, product design, and research professionals.

Methods

Fifteen subjects performed 5 repetitions of two types of tasks: (1) activities of daily living and, (2) dexterity tests. The tasks were selected as representative of activities requiring the performance of the most commonly used grasping patterns[5], [63]. A ten-camera opto-electronic system (Vicon, UK) measured trajectories of 26 reflective markers placed on selected hand dorsum landmarks (metacarpal base, MCP joints, proximal interphalangeal joints, distal interphalangeal joints and the nail).

Planar angular profiles for flexion–extension movements of the Metacarpophalangeal, Proximal Interphalangeal and Distal Interphalangeal joints, along with Thumb Abduction were derived from the measured markers' coordinates.

Cross-correlation coefficients were calculated for the joint angles corresponding to the selected movements for all tasks across all subjects and correlation matrices were derived from these values, representing finger movement interdependencies.

Results

Correlation matrices showed patterns of higher correlation (average 0.91, s.d. +/- 0.02) between joint angles for tasks requiring manipulation of small objects. Correlation patterns from dexterity tests confirmed this tendency across all subjects.

Higher correlation coefficients between motions were related with high proficiency in the dexterity tests for all subjects, even in those tasks requiring large object manipulations. Correlation matrices from the dexterity tests showed participants with the highest test scores had higher correlation coefficients among joint angles (Avg. 0.90, s.d. +/-0.03).

Discussion

Subjects' movement correlation patterns suggest that, finger interdependency, required to proficiently complete a task, is related to the size of the object being manipulated. However, it is notable that in tasks requiring manipulation of larger objects, correlation values were lower, indicating that finger interdependencies are not necessary to accomplish all tasks proficiently.

There are convergences between new findings on kinematic synergies yielded from this study and some previous findings on hand coordination [12], [159]. The current study shows a general trend of motion interdependence decreasing with anatomical distance and also a clear relationship between finger interdependency and performance of manipulative tasks. These findings are supported by what has been found from alternative methods of finger coordination quantification[12], [20].

Conclusions and disclosure

The present study quantified finger interdependencies during several common manipulative tasks. Although such multi-joint acts could be carried out in seemingly an infinite number of ways, notable motion patterns do emerge as evidenced in this study. Correlation matrices allow for more applicable and accessible data, showing interdependencies patterns in a clear, observable representation. The study also rendered evidence to support the conjecture that while finger coordination is responsible for proficiency during manipulative tasks, finger interdependencies are not necessary for all types of tasks.

International Journal of Therapy and Rehabilitation

Analysis of finger movement coordination during the Variable Dexterity Test and comparative activities of daily living

V. González, J. Rowson, A. Yoxall

Abstract

Background/Aims: This study was aimed at analysing and comparing finger coordination patterns during the performance of the Variable Dexterity Test (VDT) and comparative daily tasks.

Methods: An optoelectronic system was used to record the joint angles of 10 healthy participants performing the VDT and daily tasks. Joint angles from digits 1 to 5 were cross-correlated across the tasks, providing a measure of the degree of finger movement coordination.

Findings: Correlation coefficients showed identifiable coordination patterns among the finger movements under analysis. Low correlation coefficients suggested the presence of independent finger movements during the performance of the selected tasks.

Conclusions: Finger movement coordination patterns observed during activities of daily living are comparable with the patterns observed during performance of the Variable Dexterity Test for the three grasping patterns analysed in the study.

Journal of Hand Therapy

Analyzing finger interdependencies during the Purdue Pegboard Test and comparative activities of daily living

V. González, J. Rowson, A. Yoxall

Abstract

Study Design: Bench and cross-sectional study.Introduction: Information obtained from dexterity tests is an important component of a comprehensive examination of the hand.

Purpose of the Study: To analyze and compare finger interdependencies during the performance of the Purdue Pegboard Test (PBT) and comparative daily tasks.

Methods: A method based on the optoelectronic kinematic analysis of the precision grip style and on the calculation of cross-correlation coefficients between relevant joint angles, which provided measures of the degree of finger coordination, was conducted on 10 healthy participants performing the PBT and 2 comparative daily living tasks.

Results: Daily tasks showed identifiable interdependencies patterns between the metacarpophalangeal joints of the fingers involved in the grip. Tasks related to activities of daily living resulted in significantly higher cross-correlation coefficients across subjects and movements during the formation and manipulation phases of the tasks (0.7-0.9), whereas the release stage produced significantly lower movement correlation values (0.3-0.7). Contrarily, the formation and manipulation stages of the PBT showed low finger correlation across most subjects (0.2-0.6), whereas the release stage resulted in the highest values for all relevant movements (0.65-0.9).

Discussion: Interdependencies patterns were consistent for the activities of daily living but differ from the patterns observed from the PBT.

Conclusions: The PBT does not compare well with the whole range of finger movements that account for hand performance during daily tasks.

Appendix C

Matlab scripts and functions

Reading Motion Capture Data

```
function h = btkReadAcquisition(filename) %#ok
%BTKREADACQUISITION Read an acquisition's file (C3D, TRC, ...)
%
%  H = BTKREADACQUISITION(FILENAME) returns the handle H of a biomechanical
%  acquisition stored in file FILENAME.  This handle is returned
%  as a double and can be only used with the btk* function.
%
%  The release of the memory associated with the handle H can be done
automatically
%  by Matlab when you use the command 'clear all', or you can use the
function
%  BTKDELETEACQUISITION.  The use of the function BTKDELETEACQUISITION is
greatly
%  advised when you are doing batch processing as Matlab does not manage
the C++
%  memory and an "Out of memory" error could be thrown.
%
%  [H, BYTEORDER] = BTKREADACQUISITION(FILENAME) returns the byte order of
the
%  file as a string. The known values are:
%   - OrderNotApplicable (In the case the file is an ASCII file).
%   - IEEE_LittleEndian
%   - VAX_LittleEndian
%   - IEEE_BigEndian
%
%  [H, BYTEORDER, STORAGEFORMAT] = BTKREADACQUISITION(FILENAME) returns the
storage
%  format of the file as a string. The known values are:
%   - StorageNotApplicable (In the case the file is an ASCII file).
%   - Float
%   - Integer

%  Author: A. Barr√©
%  Copyright 2009-2013 Biomechanical ToolKit (BTK).

% The following comment, MATLAB compiler pragma, is necessary to avoid
% compiling this M-file instead of linking against the MEX-file.  Don't
remove.
%# mex

error(generatemsgid('NotSupported'),'MEX file for BTKREADACQUISITION not
found');

% [EOF] btkReadAcquisition.m
```

Transforming global coordinates to local

```
function x2 = glob2loc(r, t, varargin)
% GLOB2LOC  Applying to P the inverse of the transf. represented by R and T
%
```

```
%     Syntax 1:  P2 = glob2loc(R, T, P),         where P is an N◊3 matrix
%     Syntax 2:  S2 = glob2loc(R, T, S, FIELDS), where S is a structure
%
% See also INVTRANSFORM, TRANSFORM, LOC2GLOB

x2 = invtransform(t, r, varargin{:}, 2);
```

Euler Rotation

Around X axis

```
function [XYZ] = Rx(XYZ,a,units)

% Rx: Rotate 3D Cartesian coordinates around the X axis
%
% Useage:   [XYZ] = Rx(XYZ,alpha,units)
%
% XYZ is a [3,N] or [N,3] matrix of 3D Cartesian coordinates
%
% 'alpha' - angle of rotation about the X axis
% 'units' - angle is either 'degrees' or 'radians'
%           the default is alpha in radians
%
% If input XYZ = eye(3), the XYZ returned is
% the rotation matrix.
%
% See also Ry Rz

% Licence:  GNU GPL, no express or implied warranties
% History:  04/2002, Darren.Weber@flinders.edu.au
%                    Developed after example 3.1 of
%                    Mathews & Fink (1999), Numerical
%                    Methods Using Matlab. Prentice Hall: NY.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if ~exist('units','var'), units = 'radians'; end

% convert degrees to radians
if isequal(units,'degrees'),
    a = a*pi/180;
end

s = sin(a);
c = cos(a);
Rx = [ 1  0  0;
       0  c -s;
       0  s  c ];

if isequal(size(XYZ,1),3),
    XYZ = Rx * XYZ;
else
    XYZ = XYZ';
    if isequal(size(XYZ,1),3),
        XYZ = [Rx * XYZ]';
    else
        error('Rx: Input XYZ must be [N,3] or [3,N] matrix.\n');
    end
end
```

```
return
```

Around Y Axis

```
function [XYZ] = Ry(XYZ,b,units)

% Ry: Rotate 3D Cartesian coordinates around the Y axis
%
% Useage:   [XYZ] = Ry(XYZ,beta,units)
%
% XYZ is a [3,N] or [N,3] matrix of 3D Cartesian coordinates
%
% 'beta'  - angle of rotation about the Y axis
% 'units' - angle is either 'degrees' or 'radians'
%           the default is beta in radians
%
% If input XYZ = eye(3), the XYZ returned is
% the rotation matrix.
%
% See also Rx Rz

% Licence:  GNU GPL, no express or implied warranties
% History:  04/2002, Darren.Weber@flinders.edu.au
%                    Developed after example 3.1 of
%                    Mathews & Fink (1999), Numerical
%                    Methods Using Matlab. Prentice Hall: NY.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if ~exist('units','var'), units = 'radians'; end

% convert degrees to radians
if isequal(units,'degrees'),
    b = b*pi/180;
end

s = sin(b);
c = cos(b);
Ry = [ c   0   s;
       0   1   0;
      -s   0   c ];

if isequal(size(XYZ,1),3),
    XYZ = Ry * XYZ;
else
    XYZ = XYZ';
    if isequal(size(XYZ,1),3),
        XYZ = [Ry * XYZ]';
    else
        error('Ry: Input XYZ must be [N,3] or [3,N] matrix.\n');
    end
end

return
```

Around Z Axis

```
function [XYZ] = Rz(XYZ,g,units)

% Rz: Rotate 3D Cartesian coordinates around the Z axis
%
```

```
% Useage:   [XYZ] = Rz(XYZ,gamma,units)
%
% XYZ is a [3,N] or [N,3] matrix of 3D Cartesian coordinates
%
% 'gamma' - angle of rotation about the Z axis
% 'units' - angle is either 'degrees' or 'radians'
%           the default is gamma in radians
%
% If input XYZ = eye(3), the XYZ returned is
% the rotation matrix.
%
% See also Rx Ry

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% History:  04/2002, Darren.Weber@flinders.edu.au
%                    Developed after example 3.1 of
%                    Mathews & Fink (1999), Numerical
%                    Methods Using Matlab. Prentice Hall: NY.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if ~exist('units','var'), units = 'radians'; end

% convert degrees to radians
if isequal(units,'degrees'),
    g = g*pi/180;
end

s = sin(g);
c = cos(g);
Rz = [ c -s  0;
       s  c  0;
       0  0  1 ];

if isequal(size(XYZ,1),3),
    XYZ = Rz * XYZ;
else
    XYZ = XYZ';
    if isequal(size(XYZ,1),3),
        XYZ = [Rz * XYZ]';
    else
        error('Rz: Input XYZ must be [N,3] or [3,N] matrix.\n');
    end
end

return
```

Obtaining vectors from markers' position

```
%Calculating link vectors from markers' coordinates
S1J1IndexMC=MrkS1J1.I1-MrkS1J1.I2;
S1J1IndexPP=MrkS1J1.I2-MrkS1J1.I3;
S1J1IndexMP=MrkS1J1.I3-MrkS1J1.I4;
S1J1IndexDP=MrkS1J1.I4-MrkS1J1.I5;
S1J1RingMC=MrkS1J1.R1-MrkS1J1.R2;
S1J1RingPP=MrkS1J1.R2-MrkS1J1.R3;
S1J1RingMP=MrkS1J1.R3-MrkS1J1.R4;
S1J1RingDP=MrkS1J1.R4-MrkS1J1.R5;
S1J1ThumbMC=MrkS1J1.T1-MrkS1J1.T2;
S1J1ThumbPP=MrkS1J1.T2-MrkS1J1.T3;
S1J1ThumbDP=MrkS1J1.T3-MrkS1J1.T4;
```

```
S1J1ThumbIndexJ=MrkS1J1.I2-MrkS1J1.T2;
S1J1MiddleMC=MrkS1J1.M1-MrkS1J1.M2;
S1J1MiddlePP=MrkS1J1.M2-MrkS1J1.M3;
S1J1MiddleMP=MrkS1J1.M3-MrkS1J1.M4;
S1J1MiddleDP=MrkS1J1.M4-MrkS1J1.M5;
S1J1LittleMC=MrkS1J1.L1-MrkS1J1.L2;
S1J1LittlePP=MrkS1J1.L2-MrkS1J1.L3;
S1J1LittleMP=MrkS1J1.L3-MrkS1J1.L4;
S1J1LittleDP=MrkS1J1.L4-MrkS1J1.L5;

S1J2IndexMC=MrkS1J2.I1-MrkS1J2.I2;
S1J2IndexPP=MrkS1J2.I2-MrkS1J2.I3;
S1J2IndexMP=MrkS1J2.I3-MrkS1J2.I4;
S1J2IndexDP=MrkS1J2.I4-MrkS1J2.I5;
S1J2RingMC=MrkS1J2.R1-MrkS1J2.R2;
S1J2RingPP=MrkS1J2.R2-MrkS1J2.R3;
S1J2RingMP=MrkS1J2.R3-MrkS1J2.R4;
S1J2RingDP=MrkS1J2.R4-MrkS1J2.R5;
S1J2ThumbMC=MrkS1J2.T1-MrkS1J2.T2;
S1J2ThumbPP=MrkS1J2.T2-MrkS1J2.T3;
S1J2ThumbDP=MrkS1J2.T3-MrkS1J2.T4;
S1J2ThumbIndexJ=MrkS1J2.I2-MrkS1J2.T2;
S1J2MiddleMC=MrkS1J2.M1-MrkS1J2.M2;
S1J2MiddlePP=MrkS1J2.M2-MrkS1J2.M3;
S1J2MiddleMP=MrkS1J2.M3-MrkS1J2.M4;
S1J2MiddleDP=MrkS1J2.M4-MrkS1J2.M5;
S1J2LittleMC=MrkS1J2.L1-MrkS1J2.L2;
S1J2LittlePP=MrkS1J2.L2-MrkS1J2.L3;
S1J2LittleMP=MrkS1J2.L3-MrkS1J2.L4;
S1J2LittleDP=MrkS1J2.L4-MrkS1J2.L5;

S1J3IndexMC=MrkS1J3.I1-MrkS1J3.I2;
S1J3IndexPP=MrkS1J3.I2-MrkS1J3.I3;
S1J3IndexMP=MrkS1J3.I3-MrkS1J3.I4;
S1J3IndexDP=MrkS1J3.I4-MrkS1J3.I5;
S1J3RingMC=MrkS1J3.R1-MrkS1J3.R2;
S1J3RingPP=MrkS1J3.R2-MrkS1J3.R3;
S1J3RingMP=MrkS1J3.R3-MrkS1J3.R4;
S1J3RingDP=MrkS1J3.R4-MrkS1J3.R5;
S1J3ThumbMC=MrkS1J3.T1-MrkS1J3.T2;
S1J3ThumbPP=MrkS1J3.T2-MrkS1J3.T3;
S1J3ThumbDP=MrkS1J3.T3-MrkS1J3.T4;
S1J3ThumbIndexJ=MrkS1J3.I2-MrkS1J3.T2;
S1J3MiddleMC=MrkS1J3.M1-MrkS1J3.M2;
S1J3MiddlePP=MrkS1J3.M2-MrkS1J3.M3;
S1J3MiddleMP=MrkS1J3.M3-MrkS1J3.M4;
S1J3MiddleDP=MrkS1J3.M4-MrkS1J3.M5;
S1J3LittleMC=MrkS1J3.L1-MrkS1J3.L2;
S1J3LittlePP=MrkS1J3.L2-MrkS1J3.L3;
S1J3LittleMP=MrkS1J3.L3-MrkS1J3.L4;
S1J3LittleDP=MrkS1J3.L4-MrkS1J3.L5;

%Index finger planar joint angles
S1J1IMCPFlex=atan2(sqrt(sum((cross(S1J1IndexMC,S1J1IndexPP,2)).^2,2)),dot(S
1J1IndexMC,S1J1IndexPP,2));
S1J1IMCPFlexDeg=radtodeg(S1J1IMCPFlex);
S1J1IPIPFlex=atan2(sqrt(sum((cross(S1J1IndexPP,S1J1IndexMP,2)).^2,2)),dot(S
1J1IndexPP,S1J1IndexMP,2));
S1J1IPIPFlexDeg=radtodeg(S1J1IPIPFlex);
S1J1IDIPFlex=atan2(sqrt(sum((cross(S1J1IndexMP,S1J1IndexDP,2)).^2,2)),dot(S
1J1IndexMP,S1J1IndexDP,2));
S1J1IDIPFlexDeg=radtodeg(S1J1IDIPFlex);
```

```
S1J2IMCPFlex=atan2(sqrt(sum((cross(S1J2IndexMC,S1J2IndexPP,2)).^2,2)),dot(S
1J2IndexMC,S1J2IndexPP,2));
S1J2IMCPFlexDeg=radtodeg(S1J2IMCPFlex);
S1J2IPIPFlex=atan2(sqrt(sum((cross(S1J2IndexPP,S1J2IndexMP,2)).^2,2)),dot(S
1J2IndexPP,S1J2IndexMP,2));
S1J2IPIPFlexDeg=radtodeg(S1J2IPIPFlex);
S1J2IDIPFlex=atan2(sqrt(sum((cross(S1J2IndexMP,S1J2IndexDP,2)).^2,2)),dot(S
1J2IndexMP,S1J2IndexDP,2));
S1J2IDIPFlexDeg=radtodeg(S1J2IDIPFlex);

S1J3IMCPFlex=atan2(sqrt(sum((cross(S1J3IndexMC,S1J3IndexPP,2)).^2,2)),dot(S
1J3IndexMC,S1J3IndexPP,2));
S1J3IMCPFlexDeg=radtodeg(S1J3IMCPFlex);
S1J3IPIPFlex=atan2(sqrt(sum((cross(S1J3IndexPP,S1J3IndexMP,2)).^2,2)),dot(S
1J3IndexPP,S1J3IndexMP,2));
S1J3IPIPFlexDeg=radtodeg(S1J3IPIPFlex);
S1J3IDIPFlex=atan2(sqrt(sum((cross(S1J3IndexMP,S1J3IndexDP,2)).^2,2)),dot(S
1J3IndexMP,S1J3IndexDP,2));
S1J3IDIPFlexDeg=radtodeg(S1J3IDIPFlex);

%Thumb planar joint angles
S1J1TAbd=atan2(sqrt(sum((cross(S1J1ThumbIndexJ,S1J1ThumbPP,2)).^2,2)),dot(S
1J1ThumbIndexJ,S1J1ThumbPP,2));
S1J1TAbdDeg=radtodeg(S1J1TAbd);
S1J1TMCPFlex=atan2(sqrt(sum((cross(S1J1ThumbMC,S1J1ThumbPP,2)).^2,2)),dot(S
1J1ThumbMC,S1J1ThumbPP,2));
S1J1TMCPFlexDeg=radtodeg(S1J1TMCPFlex);
S1J1TIPFlex=atan2(sqrt(sum((cross(S1J1ThumbPP,S1J1ThumbDP,2)).^2,2)),dot(S1
J1ThumbPP,S1J1ThumbDP,2));
S1J1TIPFlexDeg=radtodeg(S1J1TIPFlex);

S1J2TAbd=atan2(sqrt(sum((cross(S1J2ThumbIndexJ,S1J2ThumbPP,2)).^2,2)),dot(S
1J2ThumbIndexJ,S1J2ThumbPP,2));
S1J2TAbdDeg=radtodeg(S1J2TAbd);
S1J2TMCPFlex=atan2(sqrt(sum((cross(S1J2ThumbMC,S1J2ThumbPP,2)).^2,2)),dot(S
1J2ThumbMC,S1J2ThumbPP,2));
S1J2TMCPFlexDeg=radtodeg(S1J2TMCPFlex);
S1J2TIPFlex=atan2(sqrt(sum((cross(S1J2ThumbPP,S1J2ThumbDP,2)).^2,2)),dot(S1
J2ThumbPP,S1J2ThumbDP,2));
S1J2TIPFlexDeg=radtodeg(S1J2TIPFlex);

S1J3TAbd=atan2(sqrt(sum((cross(S1J3ThumbIndexJ,S1J3ThumbPP,2)).^2,2)),dot(S
1J3ThumbIndexJ,S1J3ThumbPP,2));
S1J3TAbdDeg=radtodeg(S1J3TAbd);
S1J3TMCPFlex=atan2(sqrt(sum((cross(S1J3ThumbMC,S1J3ThumbPP,2)).^2,2)),dot(S
1J3ThumbMC,S1J3ThumbPP,2));
S1J3TMCPFlexDeg=radtodeg(S1J3TMCPFlex);
S1J3TIPFlex=atan2(sqrt(sum((cross(S1J3ThumbPP,S1J3ThumbDP,2)).^2,2)),dot(S1
J3ThumbPP,S1J3ThumbDP,2));
S1J3TIPFlexDeg=radtodeg(S1J3TIPFlex);


%Middle finger planar joint angles
S1J1MMCPFlex=atan2(sqrt(sum((cross(S1J1MiddleMC,S1J1MiddlePP,2)).^2,2)),dot
(S1J1MiddleMC,S1J1MiddlePP,2));
S1J1MMCPFlexDeg=radtodeg(S1J1MMCPFlex);
S1J1MPIPFlex=atan2(sqrt(sum((cross(S1J1MiddlePP,S1J1MiddleMP,2)).^2,2)),dot
(S1J1MiddlePP,S1J1MiddleMP,2));
S1J1MPIPFlexDeg=radtodeg(S1J1MPIPFlex);
S1J1MDIPFlex=atan2(sqrt(sum((cross(S1J1MiddleMP,S1J1MiddleDP,2)).^2,2)),dot
```

```
(S1J1MiddleMP,S1J1MiddleDP,2));
S1J1MDIPFlexDeg=radtodeg(S1J1MDIPFlex);

S1J2MMCPFlex=atan2(sqrt(sum((cross(S1J2MiddleMC,S1J2MiddlePP,2)).^2,2)),dot
(S1J2MiddleMC,S1J2MiddlePP,2));
S1J2MMCPFlexDeg=radtodeg(S1J2MMCPFlex);
S1J2MPIPFlex=atan2(sqrt(sum((cross(S1J2MiddlePP,S1J2MiddleMP,2)).^2,2)),dot
(S1J2MiddlePP,S1J2MiddleMP,2));
S1J2MPIPFlexDeg=radtodeg(S1J2MPIPFlex);
S1J2MDIPFlex=atan2(sqrt(sum((cross(S1J2MiddleMP,S1J2MiddleDP,2)).^2,2)),dot
(S1J2MiddleMP,S1J2MiddleDP,2));
S1J2MDIPFlexDeg=radtodeg(S1J2MDIPFlex);

S1J3MMCPFlex=atan2(sqrt(sum((cross(S1J3MiddleMC,S1J3MiddlePP,2)).^2,2)),dot
(S1J3MiddleMC,S1J3MiddlePP,2));
S1J3MMCPFlexDeg=radtodeg(S1J3MMCPFlex);
S1J3MPIPFlex=atan2(sqrt(sum((cross(S1J3MiddlePP,S1J3MiddleMP,2)).^2,2)),dot
(S1J3MiddlePP,S1J3MiddleMP,2));
S1J3MPIPFlexDeg=radtodeg(S1J3MPIPFlex);
S1J3MDIPFlex=atan2(sqrt(sum((cross(S1J3MiddleMP,S1J3MiddleDP,2)).^2,2)),dot
(S1J3MiddleMP,S1J3MiddleDP,2));
S1J3MDIPFlexDeg=radtodeg(S1J3MDIPFlex);

%Ring finger planar joint angles
S1J1RMCPFlex=atan2(sqrt(sum((cross(S1J1RingMC,S1J1RingPP,2)).^2,2)),dot(S1J
1RingMC,S1J1RingPP,2));
S1J1RMCPFlexDeg=radtodeg(S1J1RMCPFlex);
S1J1RPIPFlex=atan2(sqrt(sum((cross(S1J1RingPP,S1J1RingMP,2)).^2,2)),dot(S1J
1RingPP,S1J1RingMP,2));
S1J1RPIPFlexDeg=radtodeg(S1J1RPIPFlex);
S1J1RDIPFlex=atan2(sqrt(sum((cross(S1J1RingMP,S1J1RingDP,2)).^2,2)),dot(S1J
1RingMP,S1J1RingDP,2));
S1J1RDIPFlexDeg=radtodeg(S1J1RDIPFlex);

S1J2RMCPFlex=atan2(sqrt(sum((cross(S1J2RingMC,S1J2RingPP,2)).^2,2)),dot(S1J
2RingMC,S1J2RingPP,2));
S1J2RMCPFlexDeg=radtodeg(S1J2RMCPFlex);
S1J2RPIPFlex=atan2(sqrt(sum((cross(S1J2RingPP,S1J2RingMP,2)).^2,2)),dot(S1J
2RingPP,S1J2RingMP,2));
S1J2RPIPFlexDeg=radtodeg(S1J2RPIPFlex);
S1J2RDIPFlex=atan2(sqrt(sum((cross(S1J2RingMP,S1J2RingDP,2)).^2,2)),dot(S1J
2RingMP,S1J2RingDP,2));
S1J2RDIPFlexDeg=radtodeg(S1J2RDIPFlex);

S1J3RMCPFlex=atan2(sqrt(sum((cross(S1J3RingMC,S1J3RingPP,2)).^2,2)),dot(S1J
3RingMC,S1J3RingPP,2));
S1J3RMCPFlexDeg=radtodeg(S1J3RMCPFlex);
S1J3RPIPFlex=atan2(sqrt(sum((cross(S1J3RingPP,S1J3RingMP,2)).^2,2)),dot(S1J
3RingPP,S1J3RingMP,2));
S1J3RPIPFlexDeg=radtodeg(S1J3RPIPFlex);
S1J3RDIPFlex=atan2(sqrt(sum((cross(S1J3RingMP,S1J3RingDP,2)).^2,2)),dot(S1J
3RingMP,S1J3RingDP,2));
S1J3RDIPFlexDeg=radtodeg(S1J3RDIPFlex);

%Little finger planar joint angles
S1J1LMCPFlex=atan2(sqrt(sum((cross(S1J1LittleMC,S1J1LittlePP,2)).^2,2)),dot
(S1J1LittleMC,S1J1LittlePP,2));
S1J1LMCPFlexDeg=radtodeg(S1J1LMCPFlex);
S1J1LPIPFlex=atan2(sqrt(sum((cross(S1J1LittleMC,S1J1LittlePP,2)).^2,2)),dot
(S1J1LittleMC,S1J1LittlePP,2));
S1J1LPIPFlexDeg=radtodeg(S1J1LPIPFlex);
S1J1LDIPFlex=atan2(sqrt(sum((cross(S1J1LittleMC,S1J1LittlePP,2)).^2,2)),dot
```

```
(S1J1LittleMC,S1J1LittlePP,2));
S1J1LDIPFlexDeg=radtodeg(S1J1LDIPFlex);

S1J2LMCPFlex=atan2(sqrt(sum((cross(S1J2LittleMC,S1J2LittlePP,2)).^2,2)),dot
(S1J2LittleMC,S1J2LittlePP,2));
S1J2LMCPFlexDeg=radtodeg(S1J2LMCPFlex);
S1J2LPIPFlex=atan2(sqrt(sum((cross(S1J2LittleMC,S1J2LittlePP,2)).^2,2)),dot
(S1J2LittleMC,S1J2LittlePP,2));
S1J2LPIPFlexDeg=radtodeg(S1J2LPIPFlex);
S1J2LDIPFlex=atan2(sqrt(sum((cross(S1J2LittleMC,S1J2LittlePP,2)).^2,2)),dot
(S1J2LittleMC,S1J2LittlePP,2));
S1J2LDIPFlexDeg=radtodeg(S1J2LDIPFlex);

S1J3LMCPFlex=atan2(sqrt(sum((cross(S1J3LittleMC,S1J3LittlePP,2)).^2,2)),dot
(S1J3LittleMC,S1J3LittlePP,2));
S1J3LMCPFlexDeg=radtodeg(S1J3LMCPFlex);
S1J3LPIPFlex=atan2(sqrt(sum((cross(S1J3LittleMC,S1J3LittlePP,2)).^2,2)),dot
(S1J3LittleMC,S1J3LittlePP,2));
S1J3LPIPFlexDeg=radtodeg(S1J3LPIPFlex);
S1J3LDIPFlex=atan2(sqrt(sum((cross(S1J3LittleMC,S1J3LittlePP,2)).^2,2)),dot
(S1J3LittleMC,S1J3LittlePP,2));
S1J3LDIPFlexDeg=radtodeg(S1J3LDIPFlex);

%Create matrices with normalised joint angles
S1J1Mat=[NS1J1TAbdDeg,NS1J1TMCPFlexDeg,NS1J1TIPFlexDeg,NS1J1IMCPFlexDeg,NS1
J1IPIPFlexDeg,NS1J1IDIPFlexDeg,NS1J1MMCPFlexDeg,NS1J1MPIPFlexDeg,NS1J1MDIPF
lexDeg,NS1J1RMCPFlexDeg,NS1J1RPIPFlexDeg,NS1J1RDIPFlexDeg,NS1J1LMCPFlexDeg,
NS1J1LPIPFlexDeg,NS1J1LDIPFlexDeg];
S1J2Mat=[NS1J2TAbdDeg,NS1J2TMCPFlexDeg,NS1J2TIPFlexDeg,NS1J2IMCPFlexDeg,NS1
J2IPIPFlexDeg,NS1J2IDIPFlexDeg,NS1J2MMCPFlexDeg,NS1J2MPIPFlexDeg,NS1J2MDIPF
lexDeg,NS1J2RMCPFlexDeg,NS1J2RPIPFlexDeg,NS1J2RDIPFlexDeg,NS1J2LMCPFlexDeg,
NS1J2LPIPFlexDeg,NS1J2LDIPFlexDeg];
S1J3Mat=[NS1J3TAbdDeg,NS1J3TMCPFlexDeg,NS1J3TIPFlexDeg,NS1J3IMCPFlexDeg,NS1
J3IPIPFlexDeg,NS1J3IDIPFlexDeg,NS1J3MMCPFlexDeg,NS1J3MPIPFlexDeg,NS1J3MDIPF
lexDeg,NS1J3RMCPFlexDeg,NS1J3RPIPFlexDeg,NS1J3RDIPFlexDeg,NS1J3LMCPFlexDeg,
NS1J3LPIPFlexDeg,NS1J3LDIPFlexDeg];

%Calculating tasks cycles
%S1
CycS1J1TAD=linspace(0,100,length(NS1J1TAbdDeg));
CycS1J1TMCPFD=linspace(0,100,length(NS1J1TMCPFlexDeg));
CycS1J1TIPFD=linspace(0,100,length(NS1J1TIPFlexDeg));
CycS1J1IMCPFD=linspace(0,100,length(NS1J1IMCPFlexDeg));
CycS1J1IPIPFD=linspace(0,100,length(NS1J1IPIPFlexDeg));
CycS1J1IDIPFD=linspace(0,100,length(NS1J1IDIPFlexDeg));
CycS1J1MMCPFD=linspace(0,100,length(NS1J1MMCPFlexDeg));
CycS1J1MPIPFD=linspace(0,100,length(NS1J1MPIPFlexDeg));
CycS1J1MDIPFD=linspace(0,100,length(NS1J1MDIPFlexDeg));
CycS1J1RMCPFD=linspace(0,100,length(NS1J1RMCPFlexDeg));
CycS1J1RPIPFD=linspace(0,100,length(NS1J1RPIPFlexDeg));
CycS1J1RDIPFD=linspace(0,100,length(NS1J1RDIPFlexDeg));
CycS1J1LMCPFD=linspace(0,100,length(NS1J1LMCPFlexDeg));
CycS1J1LPIPFD=linspace(0,100,length(NS1J1LPIPFlexDeg));
CycS1J1LDIPFD=linspace(0,100,length(NS1J1LDIPFlexDeg));

CycS1J2TAD=linspace(0,100,length(NS1J2TAbdDeg));
CycS1J2TMCPFD=linspace(0,100,length(NS1J2TMCPFlexDeg));
CycS1J2TIPFD=linspace(0,100,length(NS1J2TIPFlexDeg));
CycS1J2IMCPFD=linspace(0,100,length(NS1J2IMCPFlexDeg));
CycS1J2IPIPFD=linspace(0,100,length(NS1J2IPIPFlexDeg));
CycS1J2IDIPFD=linspace(0,100,length(NS1J2IDIPFlexDeg));
CycS1J2MMCPFD=linspace(0,100,length(NS1J2MMCPFlexDeg));
```

```
CycS1J2MPIPFD=linspace(0,100,length(NS1J2MPIPFlexDeg));
CycS1J2MDIPFD=linspace(0,100,length(NS1J2MDIPFlexDeg));
CycS1J2RMCPFD=linspace(0,100,length(NS1J2RMCPFlexDeg));
CycS1J2RPIPFD=linspace(0,100,length(NS1J2RPIPFlexDeg));
CycS1J2RDIPFD=linspace(0,100,length(NS1J2RDIPFlexDeg));
CycS1J2LMCPFD=linspace(0,100,length(NS1J2LMCPFlexDeg));
CycS1J2LPIPFD=linspace(0,100,length(NS1J2LPIPFlexDeg));
CycS1J2LDIPFD=linspace(0,100,length(NS1J2LDIPFlexDeg));

CycS1J3TAD=linspace(0,100,length(NS1J3TAbdDeg));
CycS1J3TMCPFD=linspace(0,100,length(NS1J3TMCPFlexDeg));
CycS1J3TIPFD=linspace(0,100,length(NS1J3TIPFlexDeg));
CycS1J3IMCPFD=linspace(0,100,length(NS1J3IMCPFlexDeg));
CycS1J3IPIPFD=linspace(0,100,length(NS1J3IPIPFlexDeg));
CycS1J3IDIPFD=linspace(0,100,length(NS1J3IDIPFlexDeg));
CycS1J3MMCPFD=linspace(0,100,length(NS1J3MMCPFlexDeg));
CycS1J3MPIPFD=linspace(0,100,length(NS1J3MPIPFlexDeg));
CycS1J3MDIPFD=linspace(0,100,length(NS1J3MDIPFlexDeg));
CycS1J3RMCPFD=linspace(0,100,length(NS1J3RMCPFlexDeg));
CycS1J3RPIPFD=linspace(0,100,length(NS1J3RPIPFlexDeg));
CycS1J3RDIPFD=linspace(0,100,length(NS1J3RDIPFlexDeg));
CycS1J3LMCPFD=linspace(0,100,length(NS1J3LMCPFlexDeg));
CycS1J3LPIPFD=linspace(0,100,length(NS1J3LPIPFlexDeg));
CycS1J3LDIPFD=linspace(0,100,length(NS1J3LDIPFlexDeg));
```

Calculating cross-correlation coefficients between joint angles

```
[CorrB3S1,pCorrB3S1]=corrcoef(S1B3Mat);
CorrB3S1=abs(CorrB3S1);
[iB3S1,jB3S1] = find(pCorrB3S1<0.05);
idx = sub2ind(size(pCorrB3S1), [iB3S1], [jB3S1]);
SigCorrB3S1 = zeros(size(CorrB3S1));
SigCorrB3S1(idx)=CorrB3S1(idx);

[CorrBu3S1,pCorrBu3S1]=corrcoef(S1Bu3Mat);
CorrBu3S1=abs(CorrBu3S1);
[iBu3S1,jBu3S1] = find(pCorrBu3S1<0.05);
idx = sub2ind(size(pCorrBu3S1), [iBu3S1], [jBu3S1]);
SigCorrBu3S1 = zeros(size(CorrBu3S1));
SigCorrBu3S1(idx)=CorrBu3S1(idx);

[CorrCo3S1,pCorrCo3S1]=corrcoef(S1Co3Mat);
CorrCo3S1=abs(CorrCo3S1);
[iCo3S1,jCo3S1] = find(pCorrCo3S1<0.05);
idx = sub2ind(size(pCorrCo3S1), [iCo3S1], [jCo3S1]);
SigCorrCo3S1 = zeros(size(CorrCo3S1));
SigCorrCo3S1(idx)=CorrCo3S1(idx);

[CorrG3S1,pCorrG3S1]=corrcoef(S1G3Mat);
CorrG3S1=abs(CorrG3S1);
[iG3S1,jG3S1] = find(pCorrG3S1<0.05);
idx = sub2ind(size(pCorrG3S1), [iG3S1], [jG3S1]);
SigCorrG3S1 = zeros(size(CorrG3S1));
SigCorrG3S1(idx)=CorrG3S1(idx);

[CorrJ3S1,pCorrJ3S1]=corrcoef(S1J3Mat);
CorrJ3S1=abs(CorrJ3S1);
[iJ3S1,jJ3S1] = find(pCorrJ3S1<0.05);
idx = sub2ind(size(pCorrJ3S1), [iJ3S1], [jJ3S1]);
SigCorrJ3S1 = zeros(size(CorrJ3S1));
SigCorrJ3S1(idx)=CorrJ3S1(idx);
```

```
[CorrPB3S1,pCorrPB3S1]=corrcoef(S1PB3Mat);
CorrPB3S1=abs(CorrPB3S1);
[iPB3S1,jPB3S1] = find(pCorrPB3S1<0.05);
idx = sub2ind(size(pCorrPB3S1), [iPB3S1], [jPB3S1]);
SigCorrPB3S1 = zeros(size(CorrPB3S1));
SigCorrPB3S1(idx)=CorrPB3S1(idx);

[CorrVC3S1,pCorrVC3S1]=corrcoef(S1VC3Mat);
CorrVC3S1=abs(CorrVC3S1);
[iVC3S1,jVC3S1] = find(pCorrVC3S1<0.05);
idx = sub2ind(size(pCorrVC3S1), [iVC3S1], [jVC3S1]);
SigCorrVC3S1 = zeros(size(CorrVC3S1));
SigCorrVC3S1(idx)=CorrVC3S1(idx);

[CorrVP3S1,pCorrVP3S1]=corrcoef(S1VP3Mat);
CorrVP3S1=abs(CorrVP3S1);
[iVP3S1,jVP3S1] = find(pCorrVP3S1<0.05);
idx = sub2ind(size(pCorrVP3S1), [iVP3S1], [jVP3S1]);
SigCorrVP3S1 = zeros(size(CorrVP3S1));
SigCorrVP3S1(idx)=CorrVP3S1(idx);

[CorrVSB3S1,pCorrVSB3S1]=corrcoef(S1VSB3Mat);
CorrVSB3S1=abs(CorrVSB3S1);
[iVSB3S1,jVSB3S1] = find(pCorrVSB3S1<0.05);
idx = sub2ind(size(pCorrVSB3S1), [iVSB3S1], [jVSB3S1]);
SigCorrVSB3S1 = zeros(size(CorrVSB3S1));
SigCorrVSB3S1(idx)=CorrVSB3S1(idx);
```

Calculating trajectory smoothness variables from marker on Index finger

```
fxS1VSB1 = fit(TS1VSB1,MrkS1VSB1.I5(:,1),'fourier8');
fyS1VSB1 = fit(TS1VSB1,MrkS1VSB1.I5(:,2),'fourier8');
fzS1VSB1 = fit(TS1VSB1,MrkS1VSB1.I5(:,3),'fourier8');

%Velocity, acceleration, and jerk

 [VxS1VSB1,AxS1VSB1] = differentiate(fxS1VSB1,TS1VSB1);
 AxfitS1VSB1 = fit(TS1VSB1,AxS1VSB1,'fourier8');
 JxS1VSB1 = differentiate(AxfitS1VSB1,TS1VSB1);
 JxfitS1VSB1 = fit(TS1VSB1,JxS1VSB1,'smoothingspline');
 SJxS1VSB1 = JxS1VSB1.^2;
 SJxfitS1VSB1 = fit(TS1VSB1,SJxS1VSB1,'smoothingspline');

[VyS1VSB1,AyS1VSB1] = differentiate(fyS1VSB1,TS1VSB1);
 AyfitS1VSB1 = fit(TS1VSB1,AyS1VSB1,'fourier8');
 JyS1VSB1 = differentiate(AyfitS1VSB1,TS1VSB1);
 JyfitS1VSB1 = fit(TS1VSB1,JyS1VSB1,'smoothingspline');
 SJyS1VSB1 = JyS1VSB1.^2;
 SJyfitS1VSB1 = fit(TS1VSB1,SJyS1VSB1,'smoothingspline');

 [VzS1VSB1,AzS1VSB1] = differentiate(fzS1VSB1,TS1VSB1);
 AzfitS1VSB1 = fit(TS1VSB1,AzS1VSB1,'fourier8');
 JzS1VSB1 = differentiate(AzfitS1VSB1,TS1VSB1);
 JzfitS1VSB1 = fit(TS1VSB1,JzS1VSB1,'smoothingspline');
 SJzS1VSB1 = JzS1VSB1.^2;
 SJzfitS1VSB1 = fit(TS1VSB1,SJzS1VSB1,'smoothingspline');
```

```
%Integrated squared jerk -> Jerk Cost

FJerkCostS1VSB1 = trapz(SJxS1VSB1(1:63) + SJyS1VSB1(1:63) +
SJzS1VSB1(1:63));

%Duration and mean speed
 FDS1VSB1 = TS1VSB1(63);
 FVS1VSB1 = sqrt(VxS1VSB1(1:63).^2+VyS1VSB1(1:63).^2+VzS1VSB1(1:63).^2);
 FVmS1VSB1 = mean(FVS1VSB1);

%Dimensionless->Normalized Jerk Metric
 FNJMS1VSB1 = (FJerkCostS1VSB1)*((FDS1VSB1.^3)/(FVmS1VSB1.^2));

%Speed metric->Normalized mean speed->Mean of speed/Peak speed

FNSMS1B1 = FVmS1B1/(max(FVS1B1));
```

Appendix D

Cross-Correlation colour maps

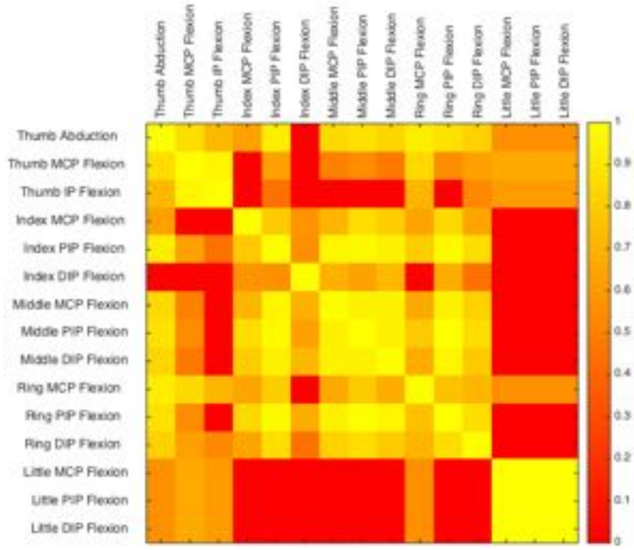

FIGURE 5.14 COLOUR MAP SHOWING THE CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 4 DURING THE MANIPULATION STAGE OF THE PURDUE PEGBOARD TEST.

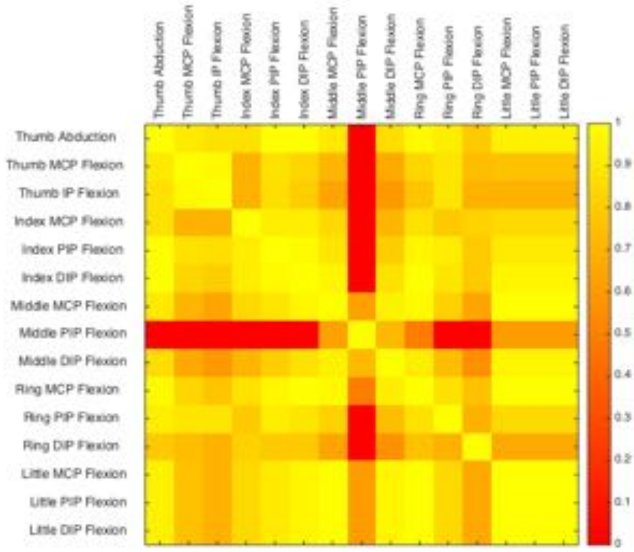

FIGURE 5.15 COLOUR MAP SHOWING THE CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 4 DURING THE RELEASE STAGE OF THE PURDUE PEGBOARD TEST.

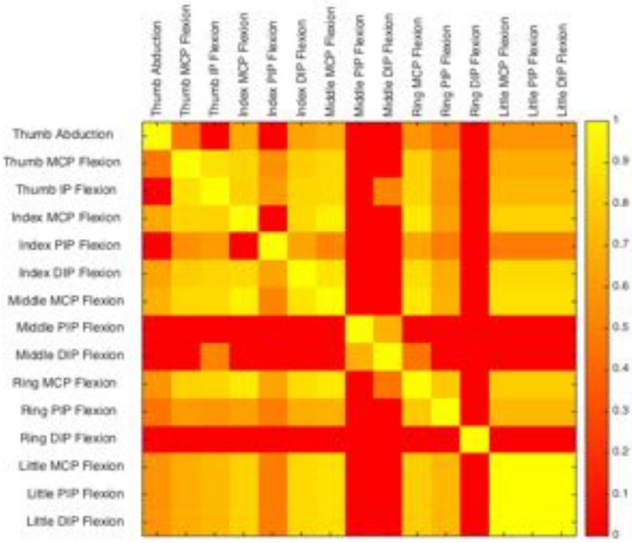

FIGURE 5.16 COLOUR MAP SHOWING THE CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 3 DURING THE RELEASE STAGE OF THE VARIABLE DEXTERITY TEST-PRECISION TASK.

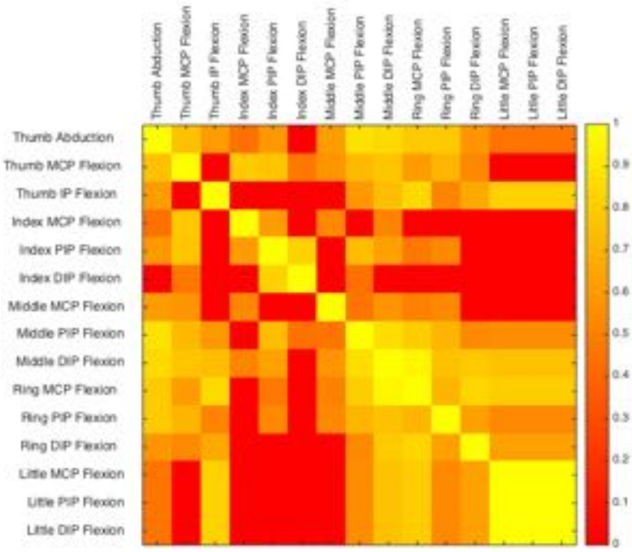

FIGURE 5.17 COLOUR MAP SHOWING THE CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 3 DURING THE MANIPULATION STAGE OF THE VARIABLE DEXTERITY TEST-PRECISION TASK.

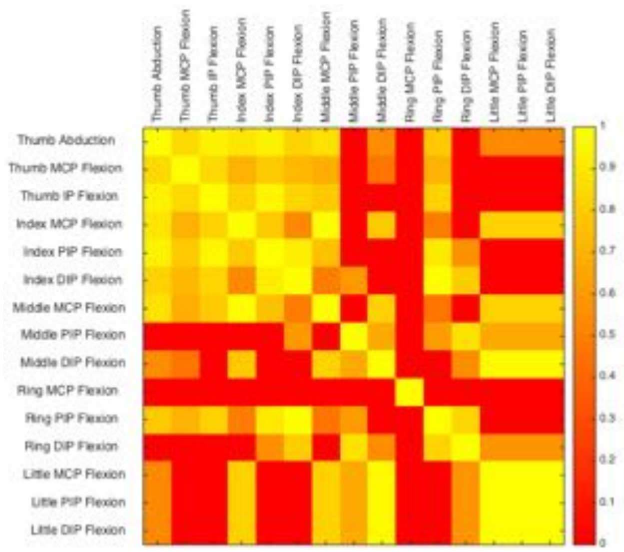

FIGURE 5.19 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 8 DURING THE FORMATION STAGE OF THE COIN TASK.

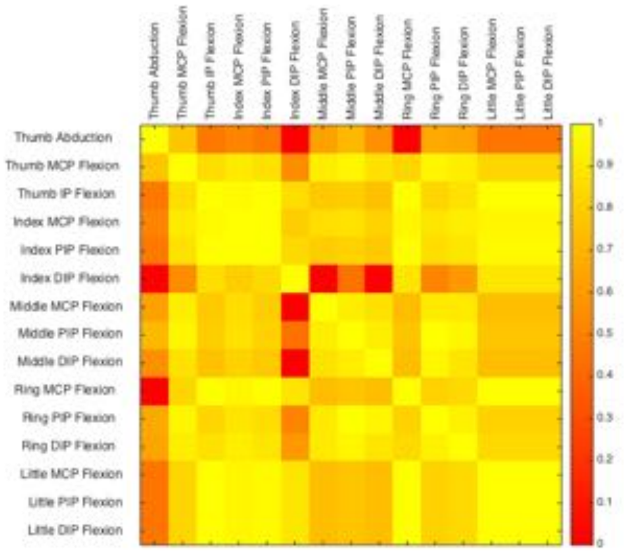

FIGURE 5.20 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 8 DURING THE MANIPULATION STAGE OF THE COIN TASK.

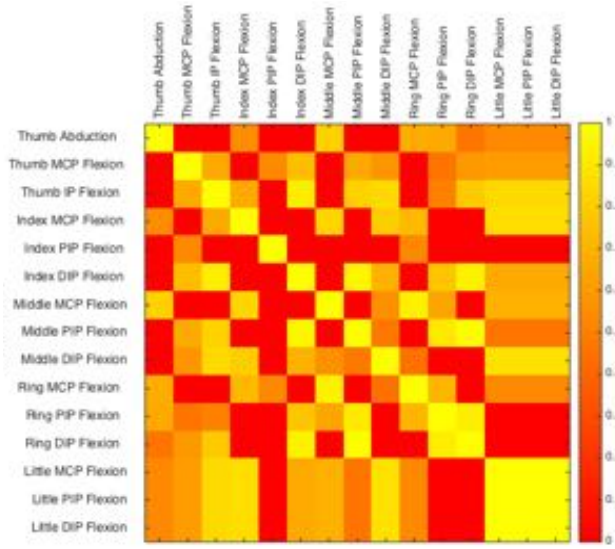

FIGURE 5.21 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 8 DURING THE RELEASE STAGE OF THE COIN TASK.

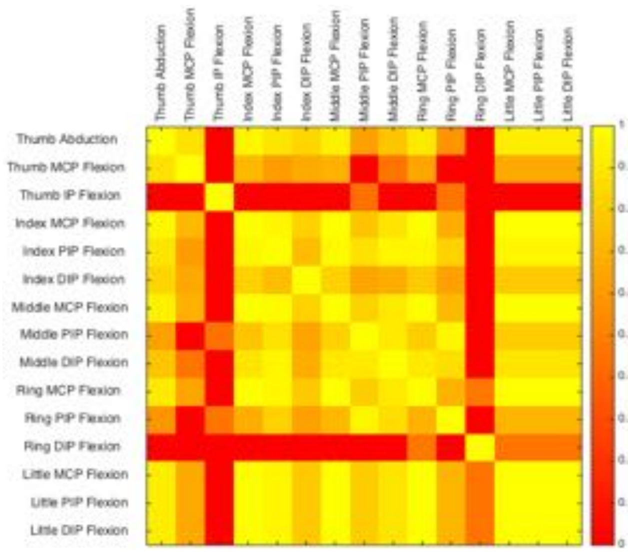

FIGURE 5.22 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 4 DURING THE FORMATION STAGE OF THE BUTTONING TASK.

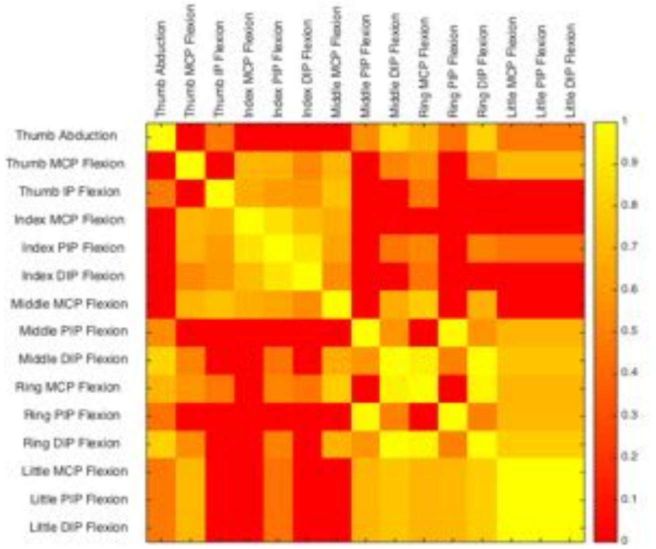

FIGURE 5.23 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 4 DURING THE MANIPULATION STAGE OF THE BUTTONING TASK.

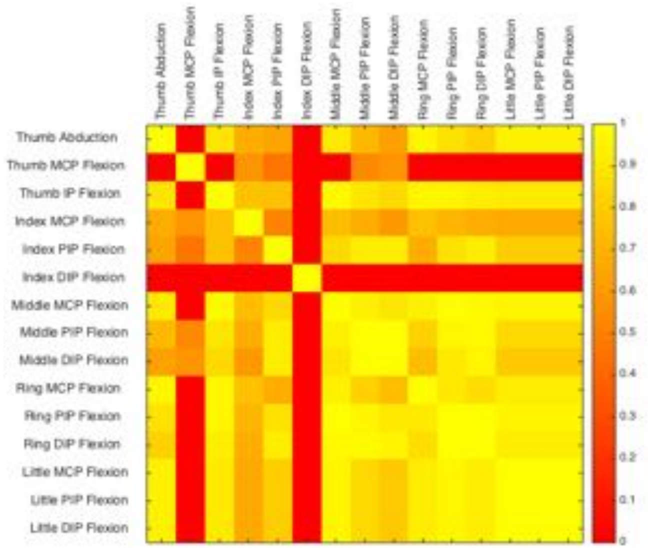

FIGURE 5.24 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 4 DURING THE RELEASE STAGE OF THE BUTTONING TASK.

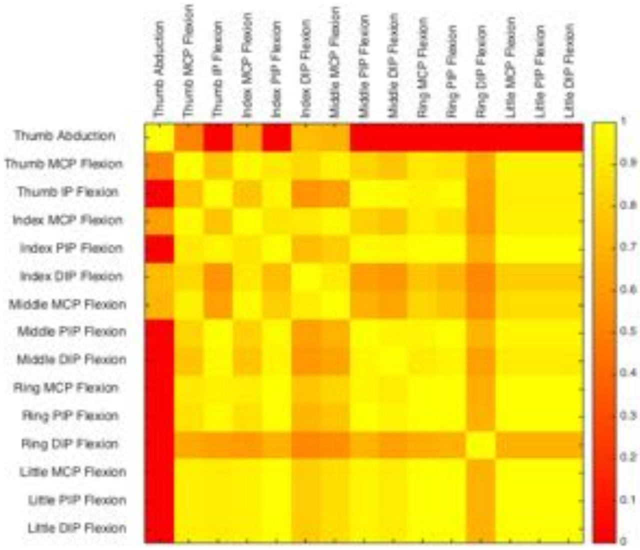

FIGURE 5.25 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 8 DURING THE FORMATION STAGE OF THE BOTTLE TASK.

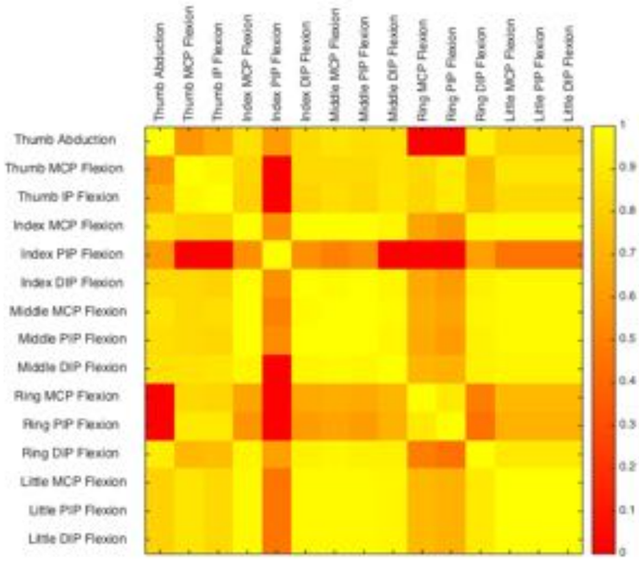

FIGURE 5.26 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 8 DURING THE MANIPULATION STAGE OF THE BOTTLE TASK.

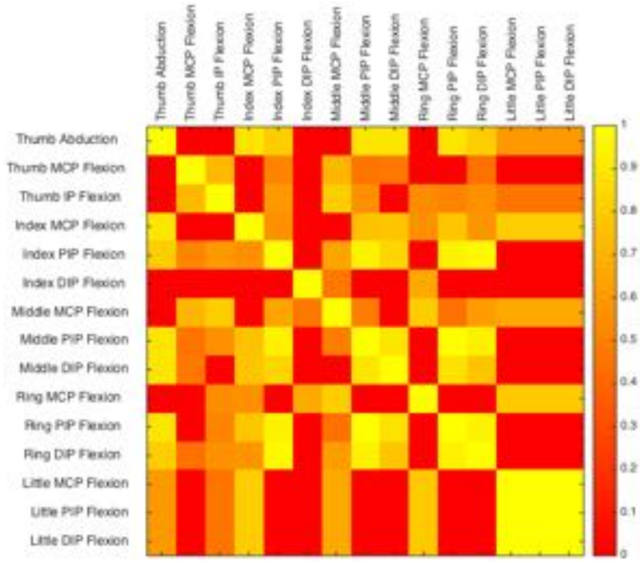

FIGURE 5.27 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 8 DURING THE RELEASE STAGE OF THE BOTTLE TASK.

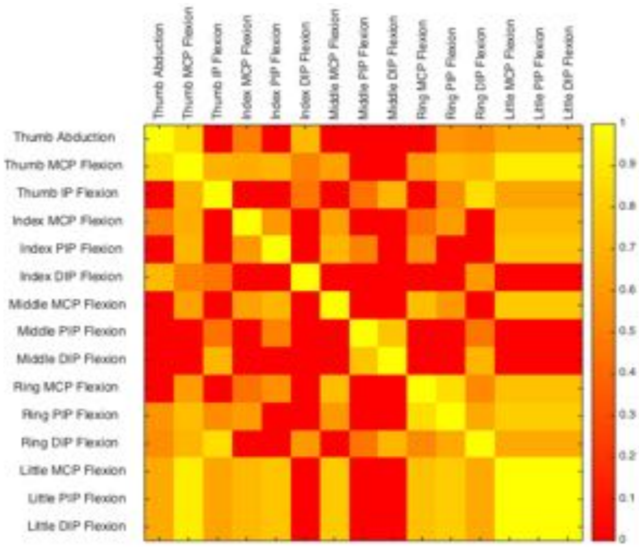

FIGURE 5.28 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 10 DURING THE FORMATION STAGE OF THE VDT-CYLINDER TASK.

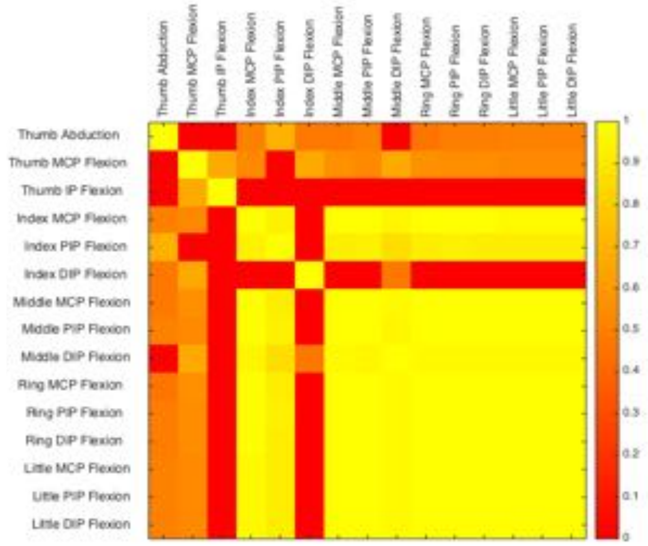

FIGURE 5.29 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 10 DURING THE MANIPULATION STAGE OF THE VDT-CYLINDER TASK.

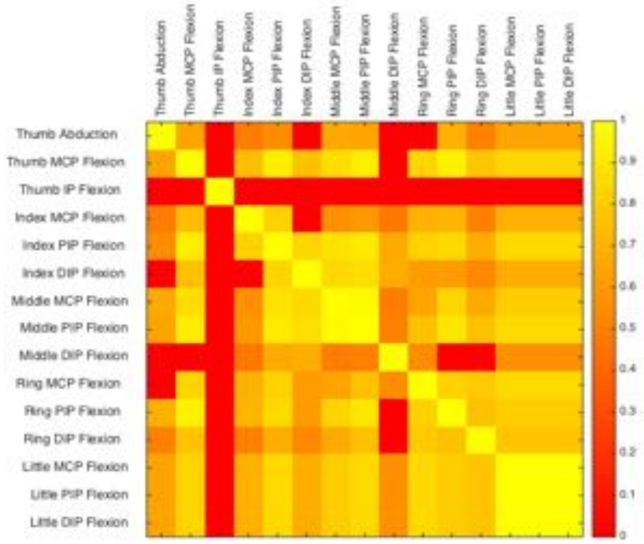

FIGURE 5.30 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 10 DURING THE RELEASE STAGE OF THE VDT-CYLINDER TASK.

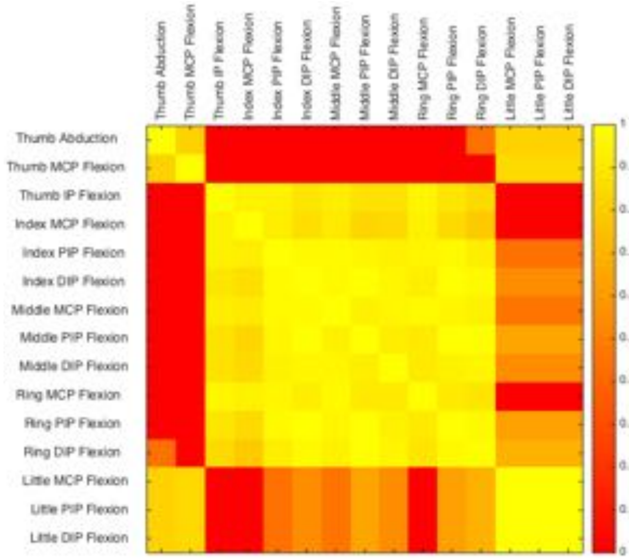

FIGURE 5.31 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 2 DURING THE FORMATION STAGE OF THE DRINKING TASK.

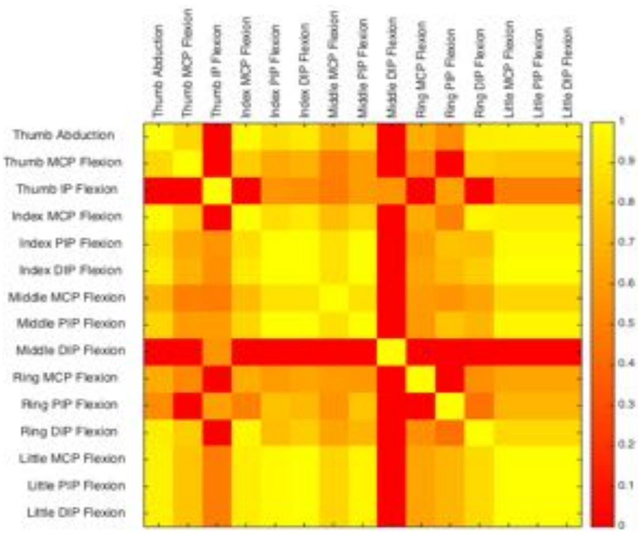

FIGURE 5.32 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 2 DURING THE MANIPULATION STAGE OF THE DRINKING TASK.

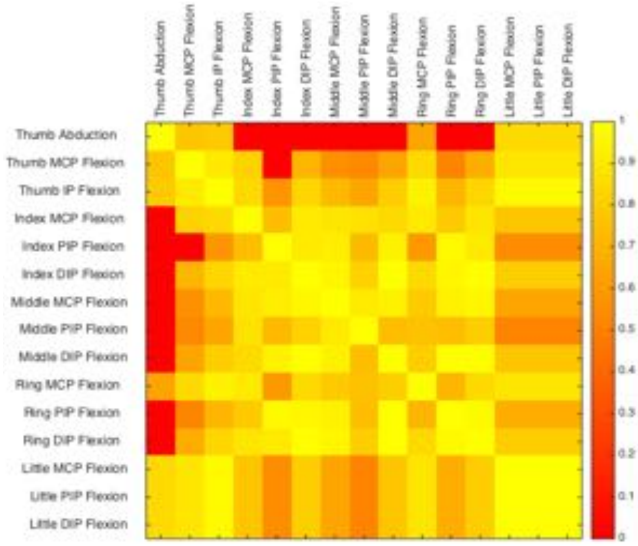

FIGURE 5.33 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 2 DURING THE RELEASE STAGE OF THE DRINKING TASK.

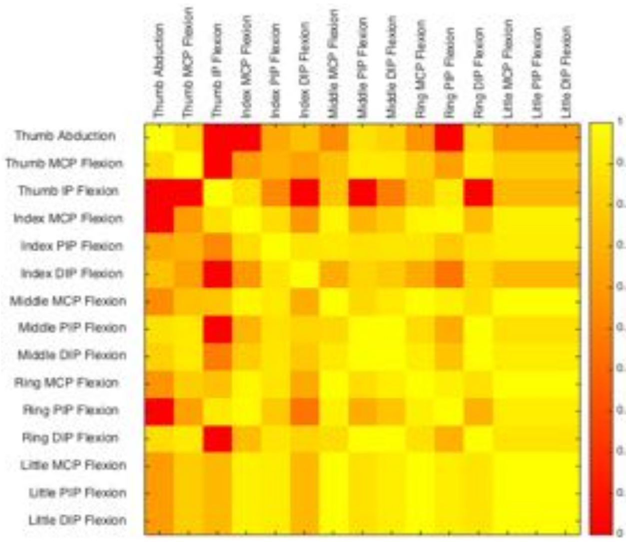

FIGURE 5.34 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 6 DURING THE FORMATION STAGE OF THE VDT-SPHERICAL TASK.

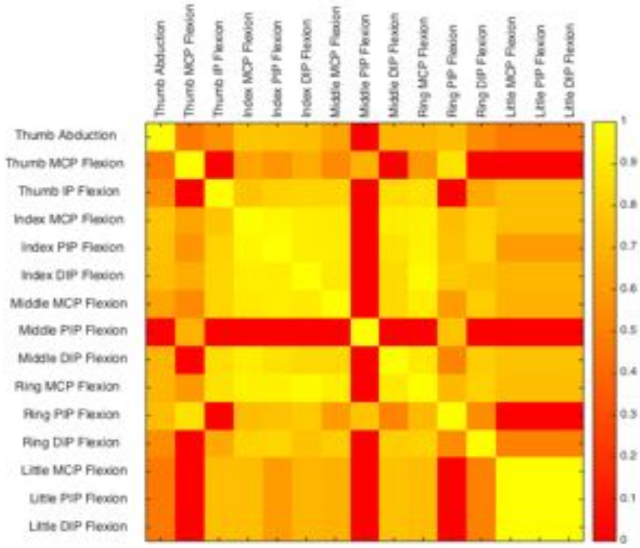

FIGURE 5.35 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 6 DURING THE MANIPULATION STAGE OF THE VDT-SPHERICAL TASK.

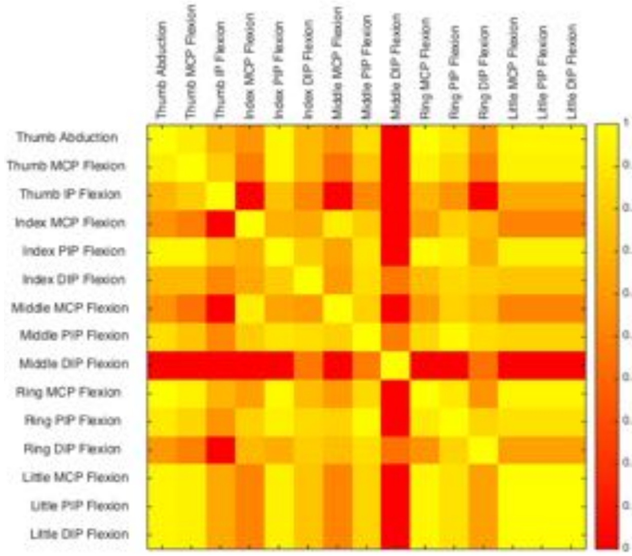

FIGURE 5.36 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 6 DURING THE RELEASE STAGE OF THE VDT-SPHERICAL TASK.

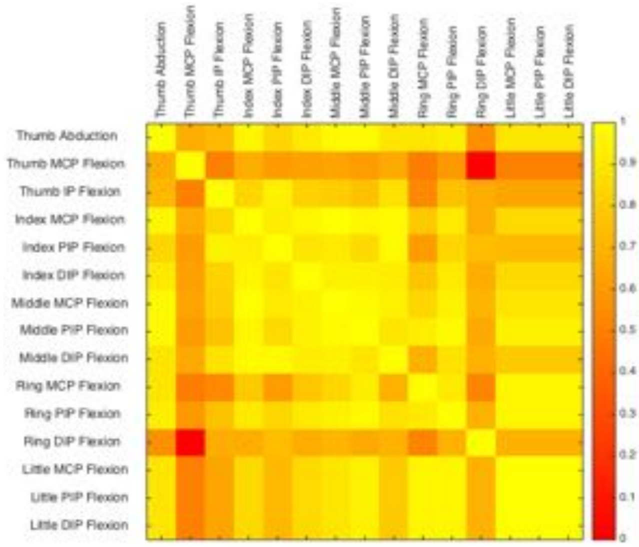

FIGURE 5.37 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 2 DURING THE FORMATION STAGE OF THE JAR TASK.

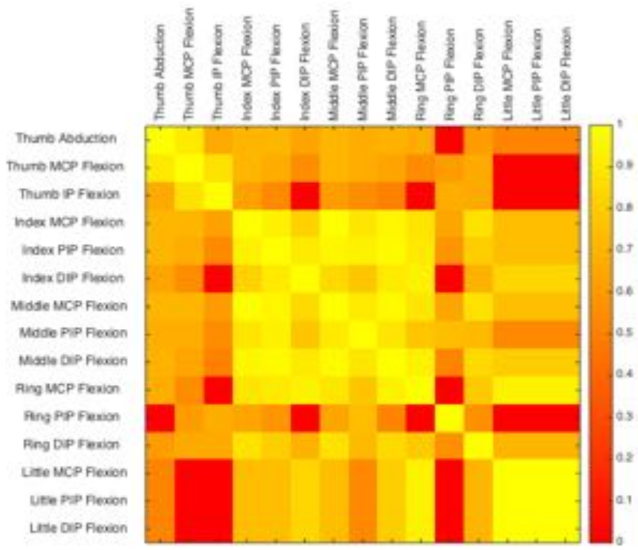

FIGURE 5.38 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 2 DURING THE MANIPULATION STAGE OF THE JAR TASK.

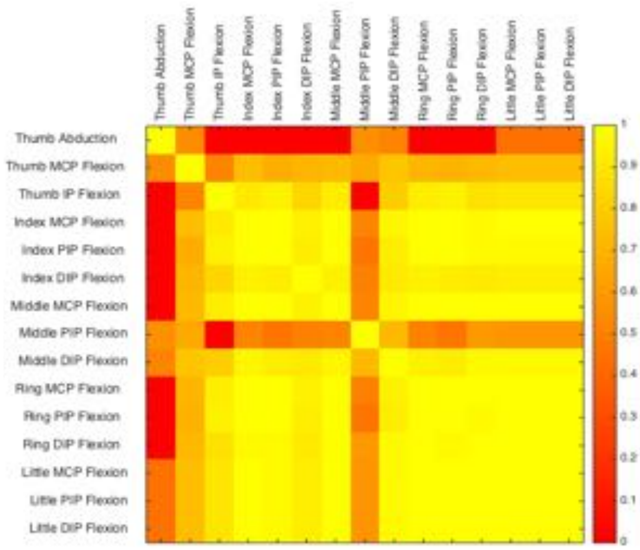

FIGURE 5.39 CORRELATION COEFFICIENTS BETWEEN MOVEMENTS FROM SUBJECT 2 DURING THE RELEASE STAGE OF THE JAR TASK.