# VISUOMOTOR BEHAVIOURS DURING FUNCTIONAL TASK PERFORMANCE WITH A MYOELECTRIC PROSTHESIS

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This thesis represents the result of almost four years of research. Since my first meeting with my supervisors, I realised how difficult and complex the research process is. However, this spurred me to work harder to make this thesis deserving of mention. Of course, this would not have happened without the tremendous support and guidance of my supervisors. Therefore, it is a pleasure to convey my gratitude to them all in this acknowledgement.

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## List of abbreviations

The following table describes the abbreviations and acronyms used throughout the thesis. The abbreviations and acronyms are in an alphabetical order. The page on which each abbreviation is defined, or first used is also given. Acronyms that are used to abbreviate the labels of the reflective markers and the names of the areas of interest are not included in the list. The acronyms of reflective markers are reported in Table 4. 2 and Table 5. 2, and of the areas of interest in Table 4. 3.

| Abbreviation | Meaning | Page |
|---|---|---|
| 2D | Two-Dimensional | 60 |
| 3D | Three-Dimensional | 4 |
| ACMC | Assessment of the Capacity for Myoelectric Control | 28 |
| ADL | Activity of Daily Living | 3 |
| ANOVA | Analysis of Variance | 93 |
| AOI | Area of Interest | 46 |
| CAST | Calibrated Anatomical System Technique | 76 |
| CI | Confidence Interval | 96 |
| CNS | Central Nervous System | 7 |
| COG | Centre of Gravity | 49 |
| DoF | Degree of Freedom | 1 |
| ECR | Elbow’s Centre of Rotation | 84 |
| EMG | Electromyographic | xiii |
| GRP | Gaze Reference Point | 54 |
| HLC | High Learning Capacity | 37 |
| HRP | Hand Resting Position | 54 |
| ICC | Intra-class Correlation Coefficient | 63 |
| ID | Index of Difficulty | 32 |
| IOF | Index of Functionality | 81 |
| JCF | Joint Coordinate Frames | 84 |
| LLC | Low Learning Capacity | 37 |
| OPUS | Orthotics and Prosthetics User Survey | 27 |
| OT | Occupational Therapist | 123 |
| PGA | Peak Grasping Aperture | 8 |
| PMES | Processed Myoelectric Signal | 22 |

| | | |
|---|---|---|
| PV | Peak Velocity | 8 |
| RMSE | Root Mean Square Error | 88 |
| ROM | Range of Motion | 35 |
| SCR | Shoulder Centre of Rotation | 84 |
| SD | Standard Deviation | 63 |
| SHAP | Southampton Hand Assessment Procedure | 27 |
| SMAS | Salford Motion Analysis System | 83 |
| TAPES | Trinity Amputation and Prosthesis Experience Scales | 27 |
| UEFS | Upper Extremity Functional Status | 27 |
| V session | Visuomotor session | 75 |

**Abstract**

Myoelectric hand prostheses are controlled via electromyographic (EMG) signals measured at the residual forearm musculature. Active functional use requires control of force and motion of the prosthetic hand in the absence of proprioceptive and tactile feedback from the hand. Many amputees often choose not to use their prosthesis in this way in everyday life. Current clinical tools provide little insight into why this is, and the few studies of motor control strategies and motor learning provide only a very partial explanation. Further studies are therefore required to inform the development of new prostheses and improved training protocols. Moreover, despite the general agreement that amputees compensate for missing proprioception through vision, at the start of the PhD there were no studies of gaze behaviour in upper limb amputees. The aims of the thesis were to:

1. To identify visuomotor behaviours that change over learning to use a myoelectric prosthesis and;

2. To identify the visuomotor behaviours of established users of myoelectric prostheses and their relationships with results from validated clinical evaluation tools.

To allow investigation of visuomotor behaviours, an everyday task was chosen, namely reaching for and acquiring a carton, then pouring water from it into a glass. A novel coding scheme for objective analysis of gaze data during task performance was developed and validated. Additionally, methods for describing upper limb kinematics were implemented. Using these tools a study of learning to use a myoelectric prosthesis simulator in anatomically intact subjects revealed a number of variables whose values change dramatically with the introduction of the prosthesis and remain different from baseline, even after practice. For example, subjects remained slower at reaching and more variable in their movement and gaze behaviour. Additionally, subjects had to pay considerable attention to the immediate task requirements. The latter findings may be interpreted as showing that prosthesis use may be attentionally demanding. A second study was then carried out involving established trans-radial myoelectric prosthesis users. Similar behaviours to those reported in the first study (following only a very brief period of practice) were observed, giving insight into why current prostheses remain difficult to use in everyday life; amputees had to pay a high degree of visual attention to the immediate requirements of the task, thus limiting their ability to plan subsequent actions of the task. Additionally, subjects who performed well on the task, were also found to perform well on the clinical evaluation tools.

# Chapter 1: Introduction

Trans-radial myoelectric prostheses are mechatronic devices designed with the aim of replacing both the function and appearance of the missing anatomy. They possess one or two active degrees of freedom, each of which is controlled via electromyographic (EMG) signals measured at the residual forearm musculature. The degrees of freedom (DoF) typically relate to hand opening and wrist rotation. To achieve functional goals, such as object acquisition and manipulation, the user must be capable of controlling the relevant EMG signal(s) so as to operate the prosthetic hand in synergy with remaining, more proximal joints. EMG control must be accomplished in the absence of proprioceptive feedback from the hand and wrist, a key source of information for the planning and execution of upper limb functional tasks in anatomically intact individuals (1).

It is clear that, despite considerable research and development over the years, current devices do not fully replace the functions of the anatomical hand (2) and poor clinical outcomes are common (3). For example, it has recently been reported that at least 20% of adult myoelectric prosthesis users reject their prosthesis, a figure which is similar to that reported more than 20 years ago (3).

Many different tools to evaluate upper limb prostheses have been developed over the years. Those can be broadly categorised into two groups: tools for measuring a user's performance on particular functional tasks and questionnaire or interview-based tools to evaluate, for example, users' perceptions of their prosthesis and the extent to which they make use of their prosthesis (4). Useful information regarding prosthetic hand performance and usage can be determined with such evaluation tools, and they are well-suited to comparison studies.

However, despite work in the area of upper limb motor control in prosthesis users carried out in the early 1980s (5, 6), there have been surprisingly few studies describing the characteristic changes in motor behaviour, and no previous work on visuomotor behaviour, associated with learning to use a prosthesis. This is despite the widespread agreement regarding the role of the vision in prosthetic use (6-10). Therefore, nothing is known about the relationships between visuomotor skill level and more clinically relevant measures, such as usage of the device in everyday life and acceptance of the prosthesis. Studies in the area of visuomotor control may lead to the development of improved outcome measures, improved designs and new training approaches.

The two aims of this thesis are:

1. To identify visuomotor behaviours that change over learning to use a myoelectric prosthesis and;

2. To identify the visuomotor behaviours of established users of myoelectric prostheses and their relationships with results from validated clinical evaluation tools.

**Chapter 2** introduces the background to the thesis. Upper limb anatomy and functions are briefly introduced to the reader. Following on from this, the concepts of motor control and skill acquisition are discussed. For this purpose, the normal visuomotor behaviour in reaching and grasping, and more complex, multi-stage tasks are described. This is followed by a brief review of the literature on learning to control hand-held tools.

In the second part of Chapter 2, the focus is on control of myoelectric prostheses. The section begins with an overview of amputation, its consequences and prosthetic management, with a particular focus on myoelectric prostheses and the reported difficulties associated with their use. The clinical evaluation tools to assess upper limb prostheses are then described and conclusions regarding their limitations are drawn. The literature on the kinematics of upper limb task performance in amputees is then discussed. Finally, the limited available literature on learning to use a prosthesis is reviewed.

Conclusions are drawn that lead on to the justification for the two major studies in the thesis – a study of visuomotor behaviours in anatomically intact subjects learning to use a myoelectric prosthesis (Chapter 4) and a study of visuomotor behaviours in amputee users of trans-radial myoelectric prostheses (Chapter 5).

**Chapter 3** describes the development of experimental approach for recording and analysing gaze behaviours during manual task performance, either using the anatomical hand or using a myoelectric prosthesis simulator. More specifically, the task to be studied is justified and defined and a coding scheme for objective analysis of the gaze data is described and its reliability assessed.

In **Chapter 4,** a study that evaluated the changes to visuomotor (kinematics and gaze) behaviours associated with learning to use a myoelectric prosthesis for the performance of an activity of daily living (ADL) task is presented. The study was conducted in anatomically intact subjects who were fitted with and practiced using a myoelectric prosthesis. The study identifies a number of visuomotor parameters which differentiate upper limb task performance with the anatomical hand from performance with a myoelectric prosthesis. Also it identifies parameters which change over learning to use the prosthesis (termed skill measures), and hence may reflect skill acquisition.

The study reported in **Chapter 5** had two aims. The first was to investigate whether the visuomotor behaviours seen in subjects using their prosthesis at the end of the study reported in Chapter 4 are also seen in amputee users of the same type of prosthesis. The second aim was to investigate the relationships between the new skill measures and current clinical measures of hand function and the extent to which amputees make use of their prosthesis in everyday life.

Upper limb unilateral amputees' use of their prosthesis was investigated using validated clinical questionnaires, and their performance on a standard, validated clinical hand function test was measured. The subjects' performance on the same task as studied in Chapter 4 was evaluated and the new skill measures for both arms were derived and compared with the findings in the study of anatomically intact subjects in Chapter 4. Finally, relationships between the established clinical outcomes and the new gaze and kinematic measures are described.

**Chapter 6** presents an overview of the entire thesis, highlights its limitations and suggests areas for future work.

## Chapter 2: Literature Review

### 2.1. Introduction

This chapter begins with an overview of the anatomical upper limb and its function. Following on from this, the literature on tool use and learning to use a tool are briefly discussed. The topics of upper limb amputation and myoelectric prostheses and their control are then introduced. This is followed by a section on outcome measures in which the clinical tools currently used to investigate upper limb prosthesis use and function are reviewed. The reader is then introduced to the literature on prosthesis functionality, acceptance and use, demonstrating that current devices remain far from ideal replacements for the anatomic hand. Finally, the studies of motor control in prosthesis users and while learning to use a prosthesis are reviewed. Finally, the need for improved prosthesis evaluation procedures is discussed, leading up to the specific aim of this thesis: development of outcome measures that characterize skill in upper limb prosthesis use in ADLs.

### 2.2. The anatomical hand and its function

The human hand allows us to manipulate objects and to interact with the environment. The complex sensory motor structure of the upper limb (including the hand) allows for goal-directed reaching with subsequent coordination and control of small muscle movements in the fingers - thereby providing us with manual dexterity (11).

With regard to the upper limb's structure, the hand can be considered the "end effector" in a chain of more proximal upper limb segments all of which contribute to its effective use as they guide it in 3D space. The upper limb in its entirety comprises 32 articulated bones (see Figure 2. 1), moved by 67 muscles (12), and contains 4 functional units (shoulder complex, elbow complex, wrist joint and hand) that allow goal-directed reach and grasp movements (13). Specifically, the shoulder complex comprises the sternoclavicular joint, acromioclavicular joint, glenohumeral joint, and scapulothoracic articulation (13) and the elbow complex consists of the humerus and ulna articulation, normally referred to as the elbow joint, and the proximal and distal radial ulnar joints (13). The wrist joint is then the complex articulation of the carpal bones with the radius, with each other, and with the metacarpal bones (13). With regard to their specific function, the shoulder and elbow joint complexes provide gross upper limb movement of the hand, and the radial ulnar and wrist joints are used to orient the hand relative to more proximal joints. Together the shoulder, elbow and wrist provide seven degrees of freedom (DoFs), thereby offering numerous solutions to a given problem of placing and orienting the hand in space. The specific function of the hand is then the act of grasping, prehension (14), and object manipulation. In pointing, the hand normally acts as an extension of the arm with no active involvement of the figures.

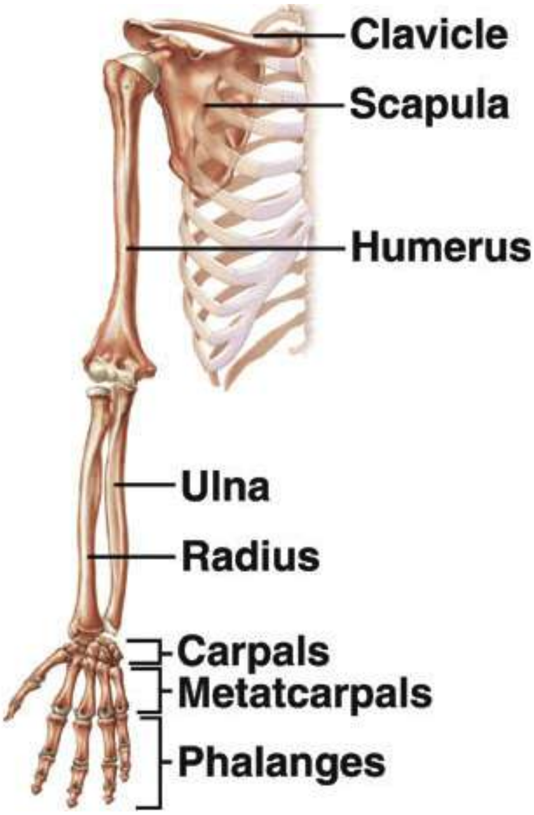


Figure 2. 1: Skeletal structure of the upper limb (adapted from (15)).

The hand (Figure 2. 2) consists of 19 bones, resulting in 17 articulations with more than 22 DoFs (16) that are controlled by 36 muscles; 19 of which originate within the hand itself and allow for fine finger movements, and 17 originate in the forearm (12). This highly evolved structure makes it possible that objects with a wide range of shapes and of different compliance can be successfully acquired and manipulated.

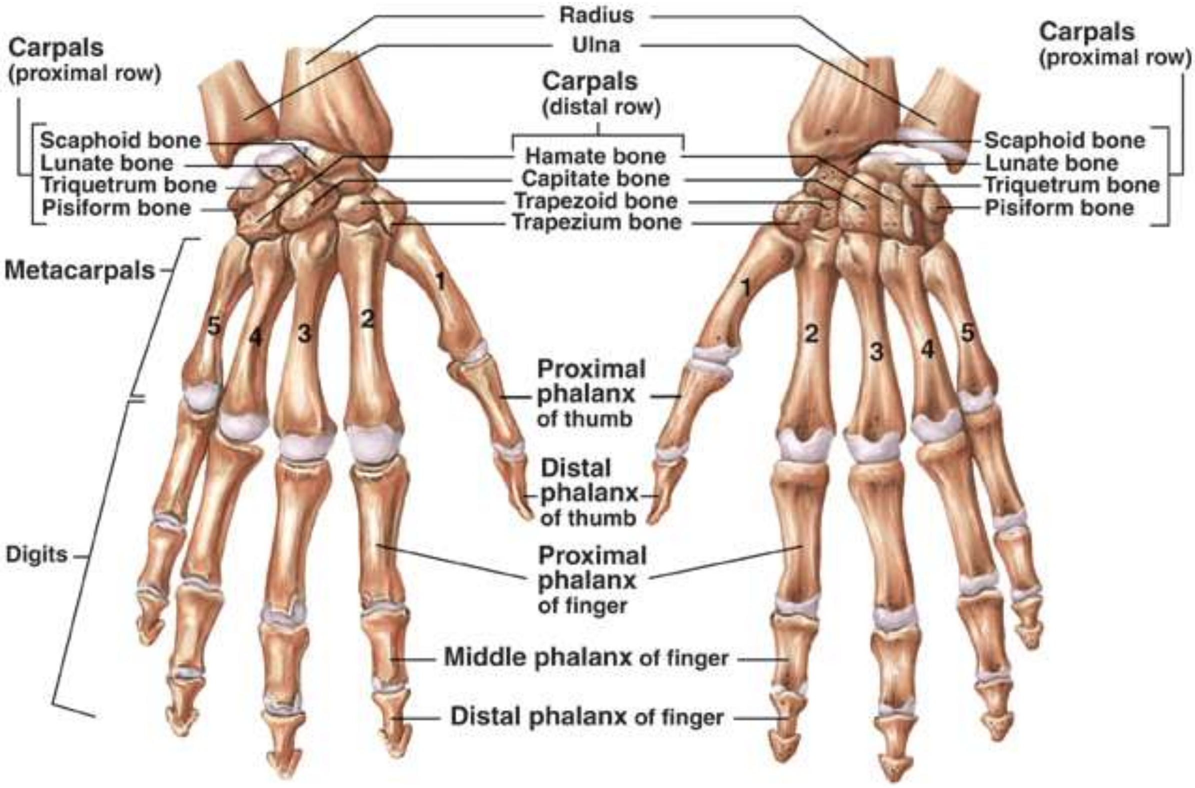


Figure 2. 2: Skeletal structure of the anatomical hand (from (15)).

With regard to the upper limb's sensory structure, the upper limb is enclosed with skin that protects the underlying musculoskeletal structures and provides a massive sensory receiver for many different sensations including pain, touch, pressure, vibration, tickle, itch, thermal changes, compliance, wetness and roughness (17). In addition, skin has a discriminative capacity which allows for object recognition (i.e. identification of an object by analysis of its size, shape, and texture). Specialised mechanoreceptors lie within the skin and provide a platform for sensory recognition. Non-hairy skin (glabrous skin), particularly palmar skin of the hand, is highly sensitive to touch allowing for excellent discriminative capacity due to its high density of mechanoreceptors (17). In fact, the pulp and skin of the fingers contains by far the highest density of mechanoreceptors in the body (17). This provides an effective mechanism for sensing the geometric properties of a grasped object and its compliance which allows fine control of grasp via grip forces (18). The mechanoreceptors also sense object slippage; they induce a reflex to increase the grip force as soon as slippage is detected (17). Although sensory information from other modalities such as vision and proprioception is employed to formulate and regulate the hand grip aperture and grip forces, the role of mechanoreceptors cannot be fully replaced by other modalities (19). Furthermore, in addition to the above discussed skin sensations, specific receptors found in skin, skeletal muscles, and joint structures enable proprioception, i.e. "to perceive sensations about position and velocity of a movement and the muscular forces generated to perform a task" (20). By far, muscle proprioceptive receptors are the most dominant source of proprioceptive feedback (17). The proprioceptive receptors of skeletal muscles respond to changes in muscle length and to the forces exerted by the muscle (17). This allows detection of movement and identification of the location of the upper limb in space in addition to estimating the object's weight in the hand (17). In addition to proprioceptive receptors found in muscles, joint capsules and ligaments comprise proprioceptive receptors that are mostly stimulated at the extreme range of motion of the joints to prevent further (harmful) movement of the joint (17).

All sensory information from the different receptors is conveyed via ascending neural pathways to the central nervous system (CNS) and motor commands are delivered via descending neural pathways in response.

Prehension, the act of grasping an object (21), is achieved using a limited number of patterns. With 7 DoFs provided by the shoulder, elbow and wrist and approximately 22 DoFs of the hand, objects can be grasped in a number of ways at any reachable location (11). The task requirement (how the object will be used) and the object's physical features (size, shape and weight) influence the grip chosen to acquire the object (22). Grips may be subdivided based on the fingers' configurations into power grip (or transversal volar grip (23)), lateral grip, tip grip, span or spherical grip, tripod grip and extension grip (Figure 2. 3) (24).

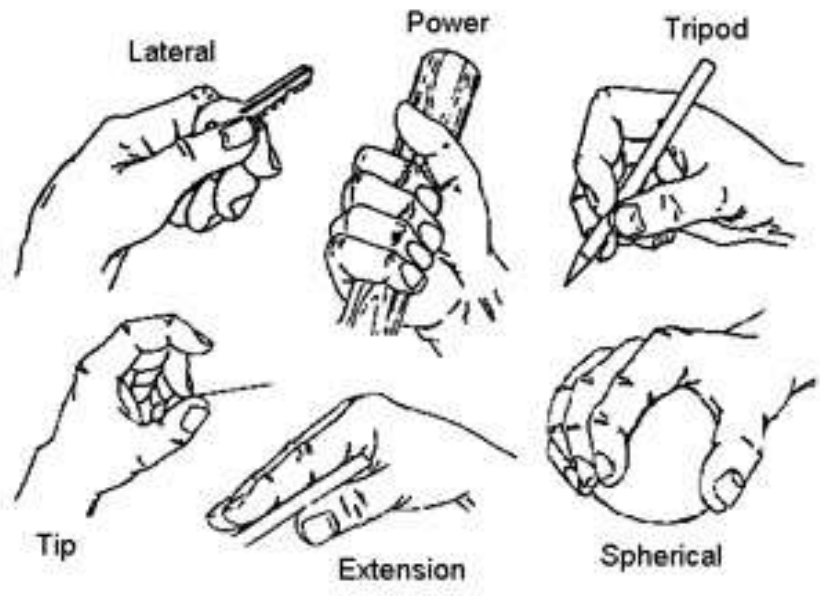


Figure 2. 3: The prehensile patterns (from (25)).

## 2.3. Reaching and manipulation

### *2.3.1. Kinematics of reaching to grasp*

When acquiring objects located within a reachable distance from the body, the hand is transferred to the vicinity of the object to be grasped by the shoulder and elbow joint motion (the reaching phase) (26). Concurrently, the hand is preshaped appropriately so the object can be grasped by the end of the reaching phase (26), this biphasic hand opening-closing motion presents the grasping component. In a functional manual task that requires reaching to grasp an object located at a fixed distance from the body, certain kinematic characteristics consistently emerge (27, 28). As illustrated in Figure 2. 4, following initiation of a reaching to grasp movement, the wrist moves rapidly to the object (acceleration phase), reaches a peak velocity (PV), then decelerates smoothly, resulting in a movement trajectory with a bell-shaped velocity profile (27, 28).

Mean and peak velocity amplitude are a function of object distance (27, 28); they increase almost linearly with the increased distance. Furthermore, both peak velocity amplitude and time to peak also decrease when reaching to grasp smaller or more fragile objects as a result of the increased accuracy demands (speed/accuracy trade-off) (29, 30). Nevertheless the bell-shaped velocity profile is maintained (30).

Hand pre-shaping and the initiation of movement of the arm toward the object start almost simultaneously (~ 50 ms lag) (27, 31). During reaching, the hand normally continues to be pre-shaped which involves configuring the fingers to achieve an aperture that is larger than the object size. The relationship between grasping aperture and the object's size was established by Marteniuk et al (32); for a 10 mm increase in object size, the grasping aperture was found to increase by 7.7 mm. Peak grasping aperture (PGA) occurs at 70-80% of the movement time; around the time of peak deceleration (11) after which the hand starts to close rapidly.

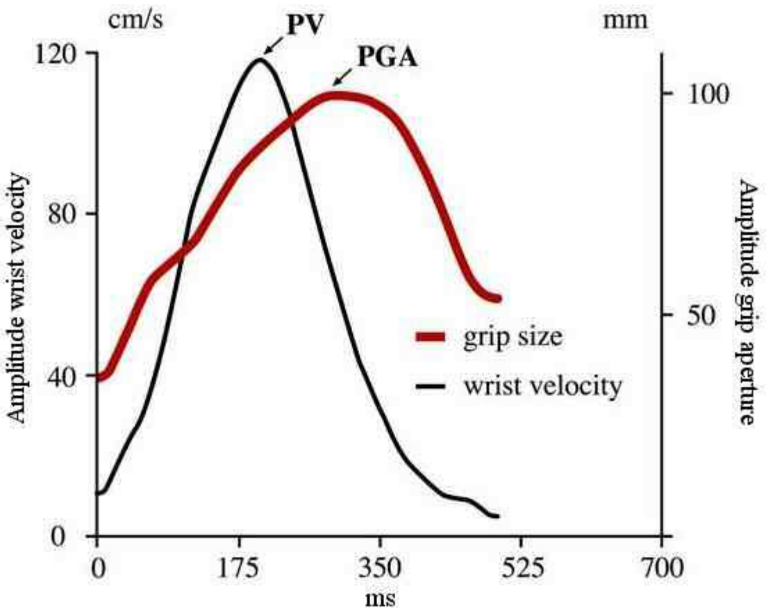


Figure 2. 4: Characteristics of reaching to grasp movement in anatomically intact individuals. The velocity profile of the wrist and the hand aperture profile are shown as a function of time. The object was a dowel (1.5 cm in diameter), located 30 cm from the subject and 20° to the right of its body midline (from (11)). Note that PV denotes peak velocity and PGA peak grasping aperture.

### *2.3.2. Vision and proprioception in reaching to grasp*

Both vision and proprioception play key roles in planning and correcting movement (1, 33). Jeannerod in his seminal works suggested that both reaching and grasping are planned based on visual information accessed during the period prior to movement initiation (27, 28, 31). According to Jeannerod, the visual information for both reaching and grasping is gathered via two independent pathways or "visuomotor channels". The independence of these two channels implies that information required to plan reaching is not used to plan grasping and vice versa. For reaching, Jeannerod demonstrated that visual information about an object's extrinsic properties (such as orientation, location and distance from the body) are used to plan the movement of the shoulder and elbow in order to move the hand towards the object. In turn, information about the object's intrinsic properties (such as shape, size and texture) is used to plan the activities of forearm and hand muscles to pre-shape the hand for grasping (27, 28, 31).

In addition to planning movement, visual feedback is essential to correct ongoing movement, particularly towards the end of the movement (34). The first evidence that suggests the visual guidance of the reaching to grasp movement came from the findings of Jeannerod (28), who reported about 1-2 cm of object undershooting in the absence of visual information about the hand location or the object, during reaching to grasp. Blocking the subject's view of the hand and/or the object for the entire movement duration were found also to introduce changes to the reaching and grasping characteristics, including an increase in reaching time (particularly due to an increase in deceleration phase duration), an increase in hand aperture duration, and increase in time to peak grip aperture (28, 33, 35-37). Interestingly, overt visual attention to the hand while reaching to grasp an object is rarely if ever seen and therefore not needed for controlling the reaching to grasp movement (38, 39). However, it seems that the visual feedback during reach to grasp comes largely from the peripheral visual field (34). Also, towards the end of the reaching movement, when the speed of the hand approaching the object is slowing, the gradual emergence of the hand into the high resolution foveal vision may be used in the control of grasp (36).

The role of proprioception in reaching and grasping is reviewed in (40). In a broad sense, proprioception provides intrinsic information about the limb; including its spatial configuration and movement, as well as muscle forces (40). This information is used by the CNS to transform the movement plan (derived from the visual information) into appropriate motor commands to the muscles (40). Proprioception information is critical for controlling intersegment coordination, as shown in a study by Sainburg et al (41). In this study, where deafferentated subjects performed an unconstrained 3D task (simulating slicing a bread loaf), they exhibited abnormally high spatial variability in their movements. Further investigation of the data revealed that this high variability was because of the temporal decoupling between the elbow and shoulder joint (41). High spatial variability (compared to control subjects) has also shown in deafferentated subject's reaching to grasp movement trajectory (33).

During reaching to grasp objects, proprioception information is also required to correct the grip formation towards the end of the movement (33). Studies in deafferentated subjects found that both the deceleration phase of the reaching movement and hand closing were extended, especially when the hand was not visually accessed (33, 42). Additionally, those subjects tend to frequently adjust the hand grasp aperture in the late stage of a reaching movement (33, 42) and exhibit a delay in hand preshaping onset when visual access to the hand is blocked (42).

## 2.4. Multi-stage functional tasks

### *2.4.1. Movement kinematics in multi-stage functional tasks*

The majority of the studies that investigated characteristics of reaching to grasping movement involved performing discrete reaching to grasp attempts under different testing conditions (i.e. different object size and distance from the subject) (11). In everyday life, however, reaching to grasp objects is usually a part of a more complex manual task; for instance, reaching to grasp objects is usually to move them, or to use them in a particular way. Interestingly, reaching to grasp kinematic characteristics are influenced by the overall intended goal of the task in a way that suggests the holistic planning of the task (30, 43). This was revealed experimentally following the original work of Marteniuk et al (30). In their work, kinematic characteristics associated with reaching to grasp an object in a "fit in a slot" task were compared with those associated with reaching to grasp of the same object in a "picking up to throw" task (30). Marteniuk et al observed a significant increase in the duration of the deceleration phase of the movement velocity profile in the "picking up to throw" task when compared to the "fit in a slot" task (30), showing the kinematics were influenced by the demands of the subsequent phase of the task. A further line of evidence to the holistic planning of the task was revealed in the study by Gentilucci et al (44) who showed that, in "pick and place" task, both reaching and grasping were affected by the distance of the target location on which the object was to be placed. With increased distance of the target, peak velocity and hand aperture increased (44). Ansuini et al (45, 46) demonstrated that in addition to the influence of the subsequent action on the hand preshaping, it also affects the positions at which the fingers make contact with the object to be grasped. In a related study, Cohen and Rosenbaum (47) argued that in multi-stage tasks, grasping position on the object is planned so it allows the subject to perform the entire task comfortably (the end-state comfort effect).

### *2.4.2. Vision in multi-stage tasks*

There have also been a number of studies of the role of vision in the execution of multi-stage, functional tasks (38, 48-52). In these studies, eye movement was directly captured using an eye tracker in order to infer the visual attention associated with task performance (discussed in more detail in Chapter 3). Land and colleagues, for instance, explored gaze behaviour in three healthy subjects making a pot of tea in a kitchen (49). In this study, in which the duration and position of gaze fixation while performing the task were described, two main findings emerged: First, that subjects only fixed their attention on areas of the scene that appeared to contain task-relevant information and secondly, that eye movement always leads the hand (49). The position at which the gaze subsequently fixates is relevant to the forthcoming action. Similar findings were reported in a study of gaze behaviour during sandwich making (51) and hand washing (48).

The role of vision in planning reaching and grasping in a multi-stage task was particularly highlighted in a study of the eye-hand coordination by Johansson et al (38). In their study, subjects were required to reach to grasp a bar one end, then move it so that the opposite end of the bar hits a target, as shown in Figure 2. 5. Subjects repeated the task 12 times, 4 times with no obstacle and 4 times each when trying to avoid one of two different obstacles placed in the direct path of the bar towards the target. Consistent with earlier findings, Johansson also found that gaze almost always fixates only at important landmarks. Further, they showed that gaze and kinematics in functional manipulation tasks were intimately linked. Specifically, the timing of gaze moving to the next landmark in the sequence was driven by key kinematic events. For example, around the time finger-bar contact was established, gaze left the grasp site area and started to move towards the other end of the bar for planning its subsequent trajectory.

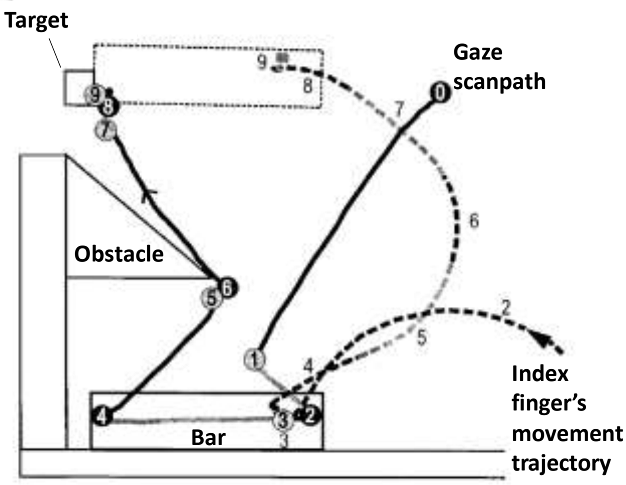


Figure 2. 5: The gaze sequence and index finger's path are shown for the task investigated by Johansson et al (38) in which a subject reached to grasp a bar and move it to a target passing an obstacle. Numbered circles indicate successive gaze fixations and numbers on the fingertip path indicate fingertip position during the corresponding gaze fixation period (from (38)).

The findings of these studies suggest that subsequent actions of a multi-stage task appear to be planned, based on visual information about these actions gathered prior to their execution (i.e. during the execution of earlier actions) (53). The visual information is retrieved by gaze fixating on a part of the scene that is relevant to the subsequent action (50). This type of gaze fixation has been termed “look-ahead fixations” (50). The location of look-ahead fixations is probably based on previous experience or through first scanning the scene (51)

In familiar multi-stage pick and place tasks, in which gaze tends to leave the object before the object being grasped starts to move, the final stage of grasping is completed with no direct visual feedback (54). This in turn suggests it is controlled using a spatial memory representation of the contact position on the object and/or using peripheral vision (51).

In certain multi-stages tasks that involve a non-discrete action that cannot easily be monitored by alternative sensory modalities (e.g. pouring water from a kettle in Land et al (49)), it is normal to also use vision to closely guide and monitor the ongoing performance (49). Subjects in Land’s study, for example, maintained the gaze fixation at the mug to monitor the level of water throughout the pouring action (49).

### 2.5. Learning to use a hand-held tool to reach and grasp

There are similarities in the challenges facing the user of a prosthesis and the user of hand held tools designed to grasp objects. These include adjusting to altered mass properties and limited degrees of freedom of the end effector, and greatly reduced proprioceptive and no tactile feedback from the object during grasping and manipulation. In this section, the literature on behaviours associated with reaching to grasp with hand-held tools is reviewed.

Lewis found that tool use is associated with neural activity in regions of the cortex that are commonly observed with complex movements of the hands (55). Therefore, tools seem to be represented in the brain as a functional extension of the hand and are likely to be controlled using similar neural process (55). These changes may be reflected in the observations that tool use extends visual-tactile peri-personal space (56-60), alters the somatosensory representation of the limb (61) and changes movement kinematics (61) and gaze behaviour (62).

A well-studied tool that has some similarities with a prosthesis is the mechanical grabber, a hand-held pincer-like tool that provides a grasping function and increases the reachable space (see Figure 2. 6).

Figure 2. 6: Mechanical grabber (from (63)).

When using a grabber to reach and grasp, subjects showed behaviours that were generally in agreement with the model of independent “visuomotor channels” proposed by Jeannerod (27). That is, the reaching phase appeared to be influenced by the object’s extrinsic features (e.g. object’s location and orientation) whereas the grasping phase was influenced by intrinsic features of the object (e.g. object’s size) (64). Similar to studies of reach to grasp with the hand, the velocity profile was also bell-shaped, but with the peak velocity occurring earlier in the reach (relative to the movement time) when compared to anatomical hand reaching to the same object placed at the same distance from the hand (64-66). For example time to peak velocity was found to be 40% in (66) and 45% in (65) of the overall time when using the tool and 49% and 48% respectively when using the anatomical hand. The effect on normalised time to peak velocity is likely due to a lengthening in the deceleration phase rather than to an absolute decrease in the time to peak velocity (64). These observed decreases in time to peak velocity and increase in the length of the deceleration phase are consistent with a higher reliance on visual feedback during reaching to grasp when using the grabber (64, 66). The longer movement time was found when the grabber was used, compared to anatomical reaching to grasp (64-67) can be also related to the influence of grabber use on the magnitude of the peak velocity of movement; a significant decline in peak velocity when a grabber was used was consistently observed in earlier studies (64-67).

More prominent kinematic differences between tool and anatomical hand use were generally found in the grasping characteristics (61, 64, 65). Generally, when the grabber was used, a larger peak aperture compared to the anatomical hand was observed (61, 64, 65). Time to peak aperture was reached very shortly after movement initiation (61, 64, 65). Closing, in turn, mostly started only when the gripper was very close to the object and occurred over an extended period of time (64, 66). Therefore, the grabber's aperture profile was associated with a notable plateau corresponding to its peak aperture (61, 64, 66, 67), a feature that is hardly ever observed in anatomical hand performance (64, 65).

The changes to movement characteristics associated with learning to use a mechanical grabber have been investigated over a short period of practice (67). Bongers (67) showed that movement time and plateau duration gradually decreased and peak velocity steadily increased within a session of practice, but movement time remained evidently longer and peak velocity lower for the tool compared to the anatomical hand. The plateau shown in the tool's grip aperture profile also remained prominent by the end of the practice session. Nevertheless, the effects of more extended practice on movement kinematics have yet to be studied.

There have been surprisingly few studies on visual behaviours in tool use. In a study comparing expert and naive users of a laparoscope (68), Law et al found that experts in laparoscopic tool use tended to maintain a clearly defined and hence consistent gaze fixation strategy (Figure 2. 7). Experts, as the examples in Figure 2. 7 illustrate, tended to fixate at the target ahead of time and maintained gaze at the target throughout the reaching movement. Novices, tended to vary in their strategies, notably, some novices tended to pursue the tool to the target, as illustrated in Figure 2. 7 (68). This indicates that novices often required visual feedback on the tool's position to complete the task. However, tool use in these studies did not involve reach to grasp objects but rather simple pointing the distal end of the tool to a target.

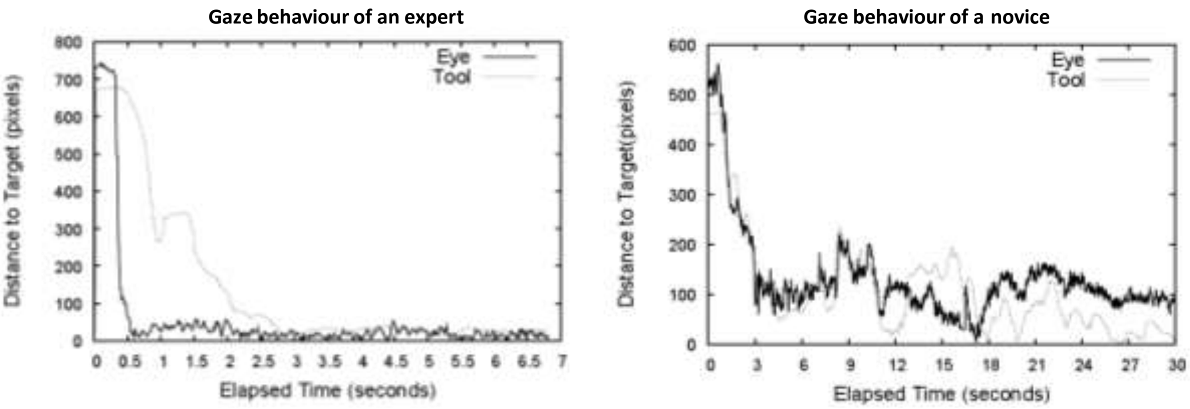


Figure 2. 7: Gaze behaviour in an expert user and a novice in the study by Law et al (68). In the graph, the distance from the target of both the tip of the tool (dotted line) and the gaze cursor (solid line) is shown as a function of time (from (68)).

In conclusion, although the brain seems to incorporate the tool in the body representation as an extension of the actual hand (55), inevitably, movement characteristics appear to be affected in ways that are consistent with higher visual demands on the immediate task. Although practice has the effect of changing movement characteristics, none of the reported, short training duration studies has found that they return to those seen in anatomical reaching to grasp. The small number of studies of visual behaviour associated with surgical tool use also suggests a reliance on visual feedback of the tool during the pointing movement, at least in naïve users (68).

## 2.6. Amputation

### *2.6.1. Levels of amputation*

An upper limb amputee is a person with an upper limb deficiency in one or both limbs (69). Limb deficiency can be the result of a problem during gestation (congenital amputation) or a result of trauma (acquired amputation). Strictly speaking, amputation is the act of cutting through one or more bones. When the cut is through the joint, the act is then referred to as disarticulation. Many conditions may lead to amputation/ disarticulation; these include peripheral vascular disease, traumas, neurologic disorders, malignant tumours, infection, and congenital deformities (70).

When amputation is inevitable, the primary goal after the removal of the diseased, damaged or dysfunctional part of the limb is to reconstruct a fast-healing, well-padded, pain-free, functional residual limb (70). Different parts of the limb may differ in shape, skin texture, and enclosed structures, amputation procedure may therefore vary (70). For the upper limb, the major levels of amputation, as seen in Figure 2. 8, from distal to proximal are: wrist disarticulation, trans-radial (below elbow), elbow disarticulation, trans-humeral (above elbow), shoulder disarticulation and forequarter amputation (71).

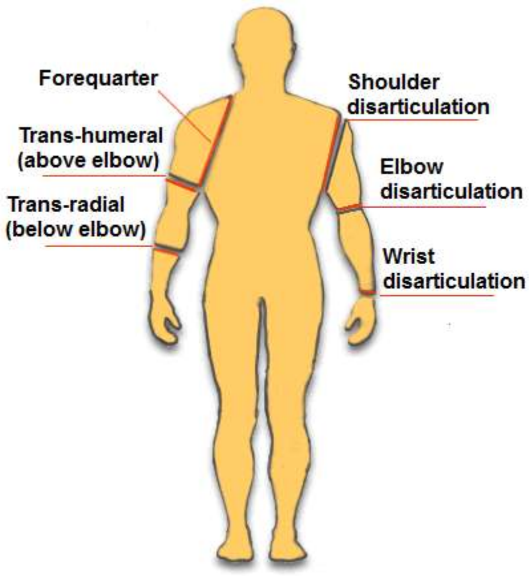


Figure 2. 8: Major level of upper limb amputation (from (72)).

When the hand is completely lost, the wrist disarticulation is the most preferable level of amputation as it preserves the supination-pronation motion of the forearm (70). However, the resulting residual limb may not be ideal for prosthetic fitting due to its bulbous end and the lack of room for accommodating the wrist and prosthetic hand (70). When wrist disarticulation is impossible, trans-radial amputation is the second best choice. Trans-radial amputation involves a cut through the forearm's radius and ulna; preferably performed at the junction of the distal and middle third of the forearm (70). This allows for adequate wound healing with maintaining enough length to suspend a prosthesis and tolerate its load (70). Although the distal radioulnar joint no longer exists at this level of amputation, some degree of supination-pronation motion may be maintained (70).

### *2.6.2. Incidence of upper limb amputation*

It is difficult to estimate the actual incidence of upper limb amputation worldwide since many countries do not keep a record of the number of individuals with amputation (73). However, the figures provided from demographic surveys/database in a few countries indicate that individuals with major upper limb amputation represent a very small proportion relative to the overall countries' population (74, 75) and to the overall number of amputees (76-78). For instance in the United States of America, of the 1.6 million amputees reported in 2005 (76), only 41000 had a major upper limb amputation which accounts for only 8% of the amputee's population (76) and 0.0001% of the total USA population in 2005. In 2007, in Norway, individuals living with major upper limb amputation accounted also for only 0.0001% of the overall population (*n* = 416) (75). The UK appears to be unique in documenting the number of upper limb amputees who are referred for limb fitting centres every year (77). In the most recent dataset available, 4957 amputees were referred to limb fitting centres, and only 4.4 % (*n* =218 ) of them had a major upper limb amputation (77).

From the published demographic data (74-78), trauma emerges as the main aetiology for upper limb amputation. In the USA, 82% of upper limb amputation was caused by trauma in 2005 (76) and 84.5% in Norway in 2007 (75). In the UK, 58% of the referred upper limb amputees acquired traumatic amputation (mostly mechanical trauma) in 2006-2007 (77). The majority of upper limb amputees are male (75-78). Upper limb amputation is also most commonly acquired between 16-54 years of age (75-77); a population that is likely to be at a relatively high risk of trauma, through work or road traffic incidents.

Although the data are rather sparse, trans-radial appears to be the most common level of amputation in most countries for which data are available. In the USA, 44% of upper limb amputees have a trans-radial amputation in 2005, and 41% have a trans-humeral amputation (76). Similar percentages have been reported in Norway in 2007 (trans-radial amputees represent 43% of upper limb amputees, trans-humeral, 24% (75)). In the UK, however, 18% and 25% of the total acquired amputees who were referred to prosthetic service were with trans-radial and trans-humeral amputation respectively in 2007 (77).

### 2.7. Upper limb prostheses

All major upper limb amputations involve loss of the sensory-motor functions of the hand and wrist joint (79). Trans-radial amputation, one of the common level of amputation, is the focus of this thesis and here the ability to rotate the forearm is severely restricted or completely lost if the amputation is more proximal than half the length of the forearm (69). In an attempt restore part of the lost functions and/or body image, amputees are fitted with and trained to use upper limb prostheses. Various models are available. Cosmetic prostheses, which provide a passive replacement for a missing limb but offer no control mechanism are not discussed in this thesis. The two main prosthesis types commonly used to restore function are; 1) body-powered prostheses, i.e. prostheses that utilize movement of an anatomically intact joint to add function, and 2) myoelectrically controlled prostheses, i.e. prostheses that utilize the myoelectric signal from the residual musculature. In the following sections, these prosthetic devices of relevance to the trans-radial amputee are described in detail.

### *2.7.1. Body powered prostheses*

The basic principle of body-powered prosthesis is the use of body movements to control prosthetic components. Typically, a stainless steel Bowden cable harnessed proximally to a stationary body segment connects distally to a prosthetic component (Figure 2. 9). When the distal body segment that holds the prosthetic component (a prosthetic hand or split hook) moves away from the body, the distance between the prosthetic component and the stationary segment increases. Given that the length of the cable is fixed this causes tensional forces in the cable, which can be used to operate the prosthetic component in one direction (e.g.. open or close the hand) (70). An elastic band/spring counteracts this force and returns the component to its neutral state when the harnessed body segment returns to its neutral position. This approach to control was first introduced in the 1920s (69) and since then, and despite some improvements to harnessing and cable configurations, the control principle remains unchanged (70).

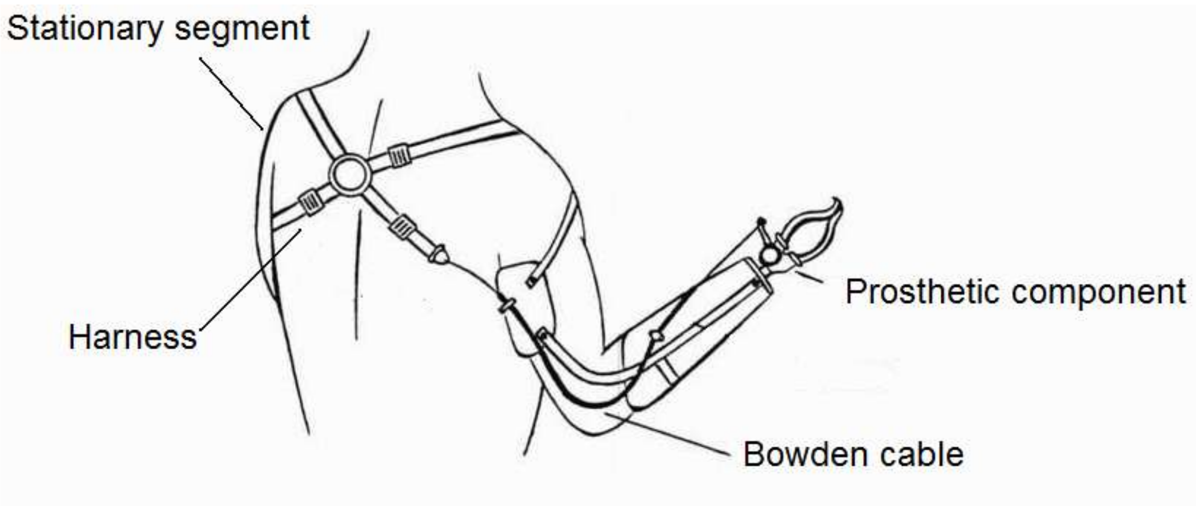


Figure 2. 9: Body powered trans-radial prosthesis (adapted from (80)).

### *2.7.2. Myoelectric prostheses*

When skeletal muscles receive a neural stimulus, a change in the polarity of the muscle fibres' membranes takes place, resulting in action potentials (electrical activity) which cause the muscle fibres to contract (12). This electrical activity is termed the myoelectric signal (or electromyographic (EMG) signal). Myoelectric signals can be detected over the contracting muscle either by invasive or surface (non-invasive) electrodes (81).

Muscle fibres in skeletal muscles are bundled in groups, and each group (so called motor unit) is innervated by a common somatic neuron. The number of muscle fibres varies between motor units, normally small units are located deep in the muscles and large unit are superficial. The force generated by a muscle contraction depends on both the number of motor units recruited and their frequency of firing (81). For a low level of contraction, predominantly deep small motor units are recruited, and for higher levels of contraction, larger and more superficial units are recruited. The EMG signal measured by surface electrodes represent the summation of action potentials from all active motor units and resembles “white noise”, see Figure 2. 10.

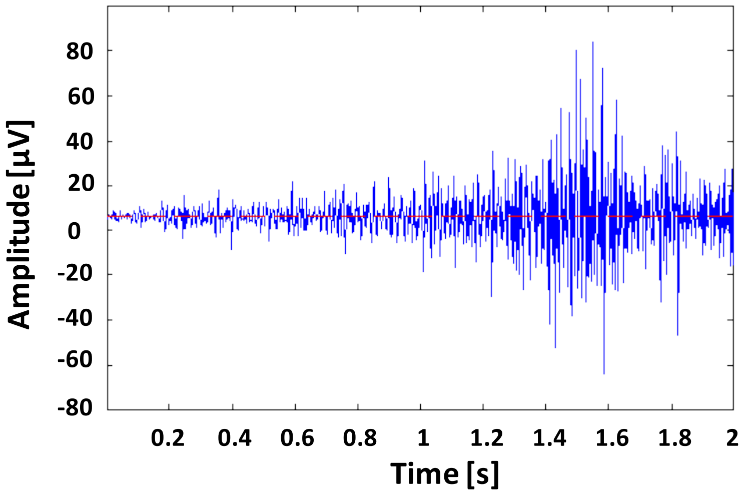


Figure 2. 10: EMG signal (adapted from (82)).

Although there has been considerable work on signal processing to extract useful information from the EMG signals (83, 84), the more advanced techniques, such as pattern recognition, have yet to be taken up by prosthesis manufacturers and hence are of little direct relevance to this thesis. In the following section the methods that have been commercially adopted for controlling myoelectric prostheses are reviewed.

As Figure 2. 10 illustrates, the amplitude of the EMG signal is very small; normally ranging between 10 µV and 10 mV (81). In order to use the signal for control, electromagnetic interference from the surrounding environment first needs to be filtered out, then the signal is amplified, rectified and filtered. The EMG signal processing is illustrated in Figure 2. 11.

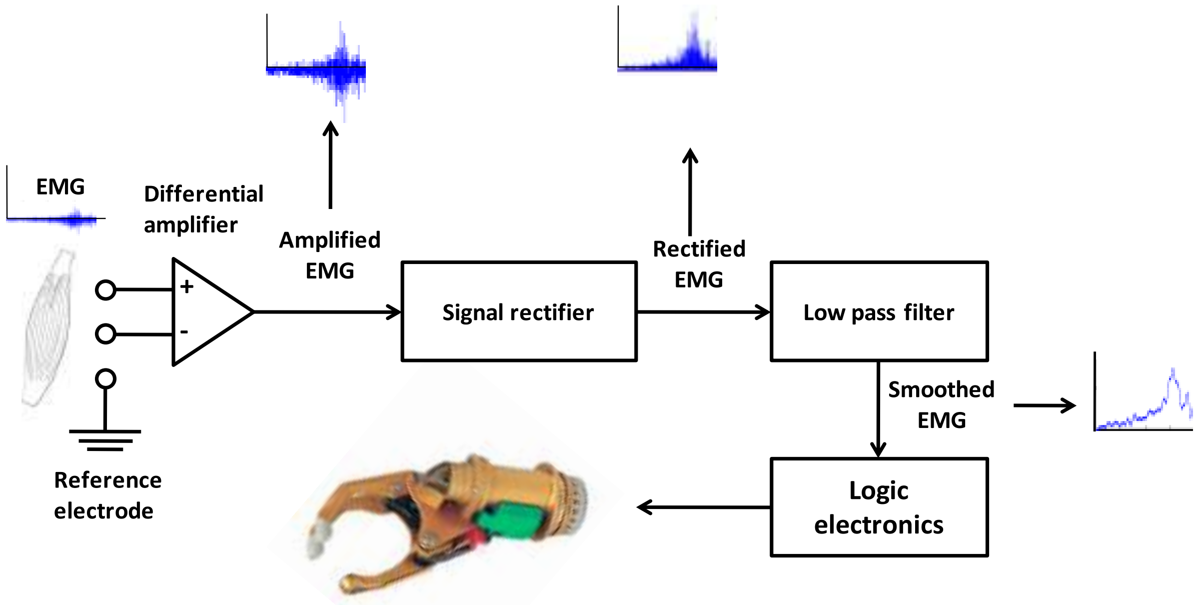


Figure 2. 11: EMG signal processing for myoelectric control.

A method that amplifies the EMG signals and attenuates the noise is required. This is achieved by using a differential amplifier. The differential amplifier amplifies the difference between the two input signals. Since the noise is equal for both inputs, considering the difference between the two signals allows the common noise to be eliminated. A schematic of the differential amplifier is illustrated in Figure 2. 12.

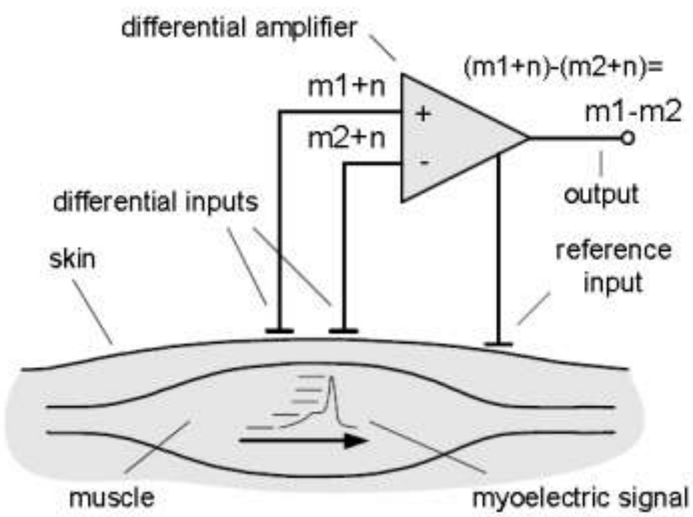


Figure 2. 12: Schematic of a differential amplifier and surface electrodes (from (85)). Note “n” is the noise common to both EMG signals m1 and m2.

Following amplification, full wave rectification followed by low pass filtering is used to produce a smooth signal that is representative of the strength of the muscular contraction. A number of different control strategies are used in commercial systems and these are briefly reviewed below.

#### 2.7.2.1. Myoelectric control strategies

*Two-site two state control strategy*

The two-site two state control strategy uses electrodes mounted on two forearm sites (flexor and extensor muscle groups) which are then processed as seen in Figure 2. 11. When the processed myoelectric signal (PMES) from the extensor muscle group exceeds a certain threshold the terminal device opens; when the flexor PMES exceeds a threshold then the hand closes. However, when both electrodes detect PMESs above the assigned threshold, as in the case of co-contraction, no action is carried out. In prosthetic devices, these thresholds are adjusted using the gain of each differential amplifier. Using this control strategy the hand is operated at a fixed velocity.

*One-site three-state control strategy*

When only one suitable muscle site is available for myoelectric control then a one-site three-state control strategy can be used as an alternative to the more physiologically natural two-site two-function control (81). This control method uses one of the features of the PMES obtained from one site to control the functions of the prosthetic component (most often the prosthetic hand). For this control strategy, two features are commonly used; the amplitude of the PMES (level or amplitude coding) or rate of change in PMES (rate coding). Both however, provide control over the hand state at a fixed velocity.

Control via amplitude coding uses two-threshold values, this divides the dynamic rage of the PMES into three regions (rest, close and open) and thereby presents three control states. When the amplitude of the PMES is below the lower threshold no action takes place with regard to the hand state; to open the terminal device the amplitude of the PMES must exceed the top threshold. When the PMES amplitude drops below the top threshold but is above the lower threshold, then the terminal device automatically closes (81).

So-called rate coding employs both, the rate of change of the PMES and its amplitude for control (81). Typically, when the mean value of the amplitude of the PMES exceeds a given threshold, the rate of change in the amplitude of the PMES is examined to select the hand state. Usually if the rate of change is high (as a result of fast muscle contraction), the hand opens and continues to open till the PMES drops below the threshold. In turn, if the rate of change is low (as a result of slow muscle contraction), the hand begins to close and keeps closing till the PMES drops below the threshold. The main disadvantage of this control strategy is the inherent time delay needed to calculate the rate of change of the PMES.

*Proportional control strategy*

A proportional control strategy enables the users to operate the prosthesis components at a velocity proportional to the amplitude of the PMES (81). Many different techniques have been introduced to control the speed proportionally. One technique is to employ amplitude coding one-site three-state control, similar to what has been described above, to select the two functions (hand opening and closing) and when the PMES is above a certain threshold, the velocity is also controlled according to the amplitude of the PMES. Alternatively, two-site two-state control can be used in the same fashion as described above to control the hand state, but using the difference in the PMES amplitude of the two sites to control the velocity of the hand.

*Microprocessor controllers*

Microprocessor controllers in general provide proportional speed control as the standard (86) and also allow easy modification of the control properties without the need for hardware adjustments. More importantly, microprocessor controllers provide a basis for more sophisticated signal processing. For example, the Southampton hand provides secure grasping of objects by automatically readjusting the grip force when object slippage is detected (87). This feature is now incorporated in the “Sensorhand Speed” produced by Otto Bock (88). The Osaka hand represents another example of an internal microprocessor controlled hand (89). The Osaka hand provides automatic adjustment of its compliance to suit the object, thus allowing soft objects to be grasped. The i-Limb™ Ultra hand from Touch Bionics Inc. is one of the very recent microprocessor controlled commercially hands (90). Among the many functional features that this hand provides is an ability to produce many different prehensile patterns by individually motorised digits. As traditional myoelectric hands, these hands also rely on only two muscle sites in their control in which users proportionally open and close the hand while different prehensile patterns however are selected by the hand microprocessor-based controller.

#### *2.7.2.2. Myoelectric controlled prosthetic components*

The first myoelectric prosthesis incorporated a simple motorised hook (81). However, the more cosmetically acceptable powered hands soon became more popular than the powered hooks (69, 81). Examples of current hands include the i-Limb™ Ultra (Figure 2. 13-A) and Select Myo Electric hand from RSL Steeper (Figure 2. 13-B) (91). When the amputee is expected to engage in dirty work situations or in heavy duty work, an electrically powered hook can be provided together with a quick disconnect wrist unit to facilitate terminal device interchanging.

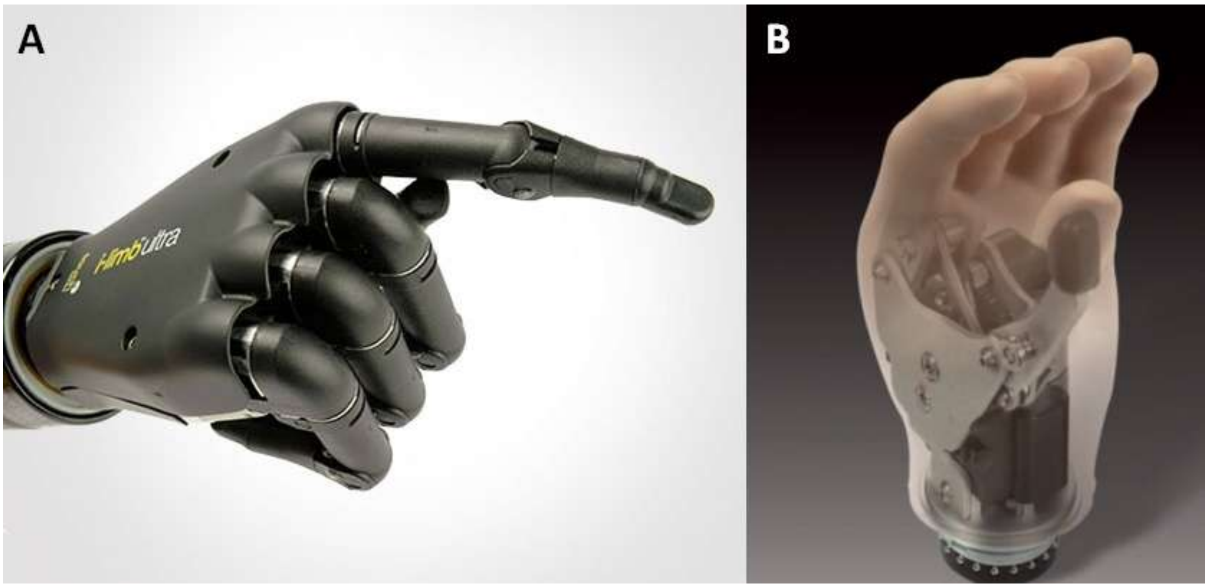


Figure 2. 13: (A) i-Limb™ Ultra from Touch Bionics (from (90)), (B) Select Myo Electric hand from RSL Steeper (from (91)).

Apart from a few very recent exceptions, such as the i-Limb Ultra from Touch Bionics Inc., almost all powered hands and hooks are now designed in a way that allows opposition of the thumb against the index and middle fingers in a tripod grip (81) (one degree of freedom), or with additional longitudinal wrist rotation (two degrees of freedom) (92, 93).

Most wrist units used with myoelectric prostheses are the same as those used with body powered prostheses and require manual positioning (69). A powered wrist is available to the most able user, which allows the user to control wrist rotation about the longitudinal axis of the forearm via EMG signals. However, their function is very limited and it has been argued that their role does not go beyond motivating the trans-radial amputee during the initial fitting period (69, 94). The reason for this is the limited number of suitable sites on the residuum for controlling the prosthesis, which are the same sites that are used to control the terminal device (81), requiring additional effort from the user to operate each function sequentially (95).

#### 2.7.2.3. *Limitations of myoelectric control*

Myoelectric prostheses retain many advantages for trans-radial amputees. The control hardware is all embedded in the prosthesis and suspension is maintained by the socket. Therefore, the prosthesis is harness free. While myoelectric prostheses also provide high grip force that is not dependent on the amputee's muscular strength they yet result in performance far inferior to that of the anatomical limb and some of the suggested reasons for this are discussed below.

Although using the EMG signals for prosthetic control is in principle physiologically natural, usually the prosthetic hand is controlled by other muscles groups than those that naturally control the anatomical hand. As discussed above, in trans-radial amputation the remaining parts of wrist flexor and extensor groups are used to control the hand (96).

Further, as introduced earlier, the remaining parts of wrist flexor and extensor groups provide at most only two sites for control. This introduces a challenging issue regarding prosthetic control: the need to control many DoFs using a very limited number of muscle sites.

Although the importance of feedback for prosthetic control was recognised shortly after the introduction of myoelectric control (97, 98), to date only a few advanced prosthetic hands are able to provide even a limited degree of automatic feedback, e.g. an automatic adjustment of the grip force when slippage is detected. Indeed, despite these advances, the vast majority of myoelectric prostheses are still basically controlled in an open loop fashion, compared to closed loop control in the anatomical hand. With the lack of proprioceptive and tactile feedback from the prosthetic hand, visual inspection may be the only approach to monitor the hand status (99) and to monitor its state.

Another limitation is control of hand orientation using a wrist rotator. The control process is unnatural because both components must be controlled using the same muscle sites, and hence can only be controlled sequentially, rather than in parallel. Therefore, continuous smooth movement is not possible when wrist rotation is required during reaching to grasp an object. Additionally, since alternation between components involves voluntarily co-contraction of both flexor and extensor muscles, it is not unreasonable to assume that this process would require further effort from the user.

## 2.8. Clinical measures of function

Restoring function is the key purpose of non-cosmetic upper limb prostheses, and perceived functional gain has been recognised as a key determining factor for prosthetic acceptance and user satisfaction (100). Successful functional restoration relies upon two aspects:

1. The extent to which the technical features of the prosthesis support the intended functions, such as being of bearable weight, having a terminal device with sufficient aperture width, grip force, and DoFs to acquire objects. This can be referred to as "engineering evaluation" and is usually ensured by the manufacturer and assessed by standard technical tests;

2. The ability of the amputee to employ these features to perform functions. Functions in this context refer precisely to the performance of manual tasks including ADLs, work-related and sport and recreational activities. This can be referred to as "functionality evaluation".

Functionality (ability to perform manual tasks) (25) is the focus of ongoing research in the field of upper limb prosthesis evaluation. In the literature, many functionality-related terms are discussed, including "functional use", "functional gain", "functional value", and "prosthetic efficiency". Functionality evaluation also varies between studies: some authors report the number of tasks that can be performed with the prosthesis (101-103) while others infer functionality from describing the quality of the performance (104-106). Alternatively, "time to complete task" is used to indicate functionality (25, 107). Functionality has been estimated by two different approaches: using interviews/questionnaires and using observational tests.

### *2.8.1. Interviews/questionnaires based evaluation of the functionality*

Interviews/questionnaires that aim to evaluate upper limb prostheses usually involve exploring qualitative aspects of the manual performance that are likely to be related to functionality. These include: "the ability to perform activities" (102), "the ease of performance with the prosthesis", "the usefulness of the prosthesis for performance" (108) and "the restrictions that the prosthesis imposes on the ability to perform" (109).

A number of questionnaires have been validated for upper limb prosthesis evaluation, but only two of them are suitable for adults; namely the Orthotics and Prosthetics User Survey with its Upper Extremity Functional Status (UEFS) module (OPUS) (105, 110), and the Trinity Amputation and Prosthesis Experience Scales (TAPES) (109).

OPUS is a questionnaire designed for evaluation of upper limb and lower limb prosthetic and orthotic users (105). It is claimed to allow comprehensive assessment of the functional status, health-related quality of life and satisfaction of the users. Each of these aspects is addressed in a self-contained module. Functionality is estimated in the Upper Extremity Functional Status (UEFS) module based on the difficulty associated with performing 19 ADLs rated on a 4 point scale (0 = not able, 1 = difficult, 2 = easy, and 3 = very easy) (110). In addition, amputees are asked to state whether or not they perform each of the tasks using their prosthesis. The UEFS list and its scoring scale have recently been revised and validated (110).

TAPES, in its original form (111), is a 54-item self-administrated questionnaire that focuses on the adaptation of the amputee to their amputation, prosthesis use, satisfaction and the level of activity restrictions that the amputee experiences in everyday life. Additionally, the TAPES assesses phantom and residual limb pain, and other medical problems unrelated to the amputation. The TAPES was originally developed for lower limb amputees and subsequently the internal reliability of the TAPES modules for assessment of upper limb amputees was established (109). Insight into functionality can be provided from two main modules that assess the level of adaptation to the prosthesis (psychological adjustment module) and level of restriction imposed by the prosthesis (activity restriction module) in functional social and athletic activities.

### *2.8.2. Clinical observational tests*

In addition to interviews/questionnaires, functionality can be assessed by evaluating the performance of the amputee in a number of manual tasks within a clinical or laboratory environment by means of observational tests. The evaluation mostly takes into consideration the time to complete the set of tasks (25) or quality of the performance based on the clinician/researcher’s judgement (108).

Several observational tests have been used to evaluate functionality of the upper limb in children and adults (see recent critical review (112)). However, only a few of them have been validated specifically for upper limb prosthetic evaluation. Of these, only the Southampton Hand Assessment Procedure (SHAP) (25) and the Assessment of the Capacity for

Myoelectric Control (ACMC) (104, 113) are suitable for upper limb prosthetic evaluation in adults.

SHAP is a universal observational test (for prosthetic or anatomical assessment) that addresses the functionality of unilateral hand in its performance (25). The SHAP comprises completion of 26 timed tasks: 12 abstract object tasks and 14 activities of daily living (ADLs). These tasks were identified in previous studies and include the natural contribution of all six prehensile patterns. When performing SHAP, subjects are instructed to use their prosthetic hand as long as the task can be achieved unilaterally, and as a main manipulator when the task is bimanual. Subjects are encouraged to use the previously mentioned 6 gripping patterns while grasping the objects. The scoring of tasks is proportional to the time needed to complete the task. Aspects of the SHAP psychometric properties have been established on normal subjects (25). The SHAP procedure is available at http://www.shap.ecs.soton.ac.uk/about-pubs.php.

SHAP has recently been used to compare the functionality of different prosthetic terminal devices (114-116). When used to compare the performance of different commercial 1 DoF myoelectric hands, SHAP also highlighted the determinant influence of the hand shape and control strategy on the overall functionality (115). For instance, the smallest hand tested (OttoBock Transcarpal hand) had a restricted gape which presented the user with difficulties in picking up large objects, and scored significantly lower on SHAP than the other hands. Interestingly, opening speed was reported to have only a limited effect on the hand's functionality (115).

In addition to providing interesting comparative data between different devices, SHAP more importantly shows how far devices are from the anatomical hand with regard to their functionality. SHAP score (usually referred to as functionality index) was found to be above 95 out of 100 when the test is completed using the dominant anatomical hand in young adults (25). In comparison, using the prosthetic hand, functionality index values range from 17 out of 100 (117) to 80 out of 100 (118).

While SHAP is a useful measure, it is based on measures of number of tasks performed and time taken to perform them (115), and hence provides no indication of how a subject performed the tasks. The ACMC was specifically developed to evaluate the ability to control the myoelectric prosthesis (108). For prosthetic evaluation it is assumed in the ACMC that the ability to control the prosthesis would be demonstrated differently while grasping, holding, releasing and co-ordinating objects and hence the ACMC focuses its evaluation on each of these phases of the task. The ACMC involves scoring of 30 items covering aspects related to the performance of any bimanual ADL including: gripping, holding, releasing, and coordinating between two hands. These items are scored based on a 4-point ordinal scale (0 = not capable, 1 = sometimes capable, capacity is not established, 2 = capable on request, and 3 = spontaneously capable). The items' scores are then converted into linear measures by using Rasch measurement models. Since these items can be observed in any bimanual ADL, any purposeful bimanual activity that is deemed meaningful to the prosthesis user can be used for this assessment. The ACMC is suitable for prosthetic evaluation in adults and children. Certain psychometric aspects have been demonstrated, including acceptable validity and good sensitivity to change (104). Recently, further work on ACMC validity has been conducted in which discriminant validity and unidimensionality of the ACMC was established (119).

ACMC has also been used in a comparative case study (114). ACMC results showed the different abilities of the user to control the i-Limb plus and DCM Otto bock hand with the superiority of the i-Limb plus. As part of the reliability investigation of the ACMC, the ACMC was also used to infer the improvement resulting from learning to control the prosthesis over a period of time (120). The investigation involved assessment of two groups of users (established users and new users) at least 6 times over a period of 18 months. The ACMC indicated high capability to use the prosthesis in established users whereas in new users a trend of improvement was demonstrated (120).

The major limitation of the ACMC is its inter-rater reliability, that is, the results of this test are strongly influenced by the experience of the scorers (113). ACMC is also limited in its myoelectric prosthesis control evaluation; therefore it is not suitable to compare different control systems or to compare prosthetic performance to anatomical hand performance. ACMC scoring may need revision (119), additionally, criteria for manual task selection are required to address the influence of task difficulty on ACMC scoring (119).

### 2.9. Usage, acceptance and rejection rates

Studies over the last decades have investigated prosthesis acceptance, as well as users' satisfaction (see review (3)). Acceptance can be defined as "making use" of the prosthesis (100), i.e. the extent to which prosthetic functions are used routinely in everyday life, which is likely associated with satisfaction of prosthesis' performance. Satisfaction represents a measure of the users' experience with the device and its functioning and high satisfaction may also be associated with prosthetic acceptance (3).

Due to the complexity associated with the term "acceptance" studies alternatively explore rejection (100). However, a clear definition of rejection has not yet been established (100). Rejection can mean complete abandonment of the prosthesis, or infrequent use of the prosthesis (100). Rejection may also include those who do not wear a prosthesis at all (non-wearers), a population about whom information is rather limited, as they are not actively involved in rehabilitation services (100). Works that have studied acceptance/rejection are concerned with two aspects:

1. The rate of rejection across the studied sample;

2. The factor that leads to prosthesis rejection.

Both, acceptance and rejection of the prostheses have previously been identified by studying the self-reported wearing pattern (103, 121, 122), i.e. the number of hours per day during which the prosthesis is worn. In cosmetic prostheses, wearing pattern is indeed a good indication of their acceptance. However, for functional prostheses, wearing pattern is not a good measure of acceptance, as the prosthesis may be worn regularly but with limited use (123, 124)

"Usage" is the extent of prosthetic use to perform tasks. Studies have investigated both active and passive usage patterns (125, 126). The satisfaction was also usually explored along with different aspect of the prosthesis such as weight, size, and comfort (9), in order to highlight the reasons for poor wear/use, where reported. All previous studies have used interviews or questionnaires (108, 122, 127-129) and although the thesis author has recently demonstrated the potential for using instrumentation to objectively monitor upper limb prosthesis activity (130), no study has so far reported on using activity monitors to objectively measure usage in free living environments (see also Appendix K).

Results from different studies showed varied prosthetic rejection rates, for instance as low as 0% (131) to as high as 75% of the sample (132). Generally, studies in this area are of poor quality, often based on small samples with unclear methodologies (3). Biddis and Chau published a recent review of studies published over the past 25 years (3) and found average rejection rates of 26% for body powered and 23% for myoelectric prostheses (3). Notably, although myoelectric prosthesis technology has undergone dramatic improvements over the past decades, reported rejection rates have not changed (3).

Biddis and Chau also reported a study investigating user views of factors influencing use and rejection (100) and found, unsurprisingly, that acceptance was higher if the prosthesis was perceived helpful in daily activities Therefore, factors such as lack of functional gain, difficulty with use, and lack of feedback seemed to be associated with prosthetic rejection (100).

## 2.10. Motor behaviours characterising upper limb myoelectric prosthesis use

In contrast to the vast number of studies of visuomotor control of the anatomical arm, the control of upper limb prostheses has not been investigated in great detail. This is probably partly due to the logistical problems with such studies; the population of upper limb prosthesis users is small, and heterogeneous, both in their impairments and choice of prosthesis. Commercial prostheses are often difficult to describe in an unambiguous manner, as the detailed control strategies often remain commercially confidential, leading to a degree of uncertainty when interpreting research papers. Even for those prosthesis users who share the same level of amputation and use the same prosthesis with the same well-described function, physical variations such as length and muscular structure of the residual limb, makes drawing generalisations on motor control strategies for a particular prosthesis user category difficult.

Nevertheless, a number of studies have attempted to characterise upper limb and prosthesis movements over a range of tasks, compared these to upper limb motions in anatomically intact populations, and reported the changes observed during learning to use a prosthesis. Studies have investigated the movement characteristics of both trans-radial (5, 7, 8, 133-139) and trans-humeral prostheses (8, 140-144). As control of trans-humeral amputees lies beyond the scope of this thesis, the following sections are limited to studies of trans-radial amputees.

### *2.10.1. Kinematics of pointing in established trans-radial amputees*

When compared with anatomically intact individuals, trans-radial amputees generally perform pointing to a target with their prosthesis under visual guidance more slowly (8) and with a lower peak velocity (7, 133). However, time to peak velocity appears to remain unchanged from normal (7). Movement trajectories of the arm tend to be as straight and smooth as in anatomically intact individuals in planar reaching (7, 133). These studies are discussed in more detail below.

Bouwsema et al (8) found that movement time increases with the index of difficulty (ID), as predicted by Fitts' Law. However, the slope of the movement time-ID curve is almost twice as steep as in anatomically intact individuals (8).

Despite the changes to the mechanical properties of the limb following amputation, the accuracy with which a target is reached with a prosthesis is not significantly different to that in anatomically intact individuals, irrespective of whether or not the hand was visually accessed during the planar pointing movement (7). In a study of a trans-radial amputee learning a more complex 3D pointing task (typing using a rod-like extension to his prosthesis), Tsukamoto observed that amputees can accurately hit targets with no visual access to the prosthesis after a relatively short period of practice (1 month). This finding was interpreted as an indication of the internal representation of the prosthesis as an extension to the arm (145). In line with these studies, recently amputee subjects have been found able to adapt to the external force perturbation at a similar rate to anatomically intact controls (133). Also when the force perturbation was randomly unexpectedly removed, amputees showed comparable to normal mean error in the movement trajectory (133).

In conclusion, although some differences between performance on pointing tasks between trans-radial and anatomically intact individuals emerged from the literature, these differences were generally limited (7). In trans-radial amputees, both the shoulder and elbow joints are intact and hence it is perhaps unsurprising that only relatively small differences in pointing between amputees and anatomically intact controls were observed.

### *2.10.2. Kinematics of reaching to grasp in trans-radial prosthesis users*

Despite the central importance of reaching to grasp, there are remarkably few studies of this behaviour in prosthesis users. Wing and Frazer (5) and a very recent study by Bouwsema et al (8) both reported on motor behaviour studies in which subjects reached towards and grasped cylindrical objects with different diameters. Wing and Frazer studied subjects using body powered, trans-radial prostheses and compared motion characteristics with the contra-lateral anatomically intact arm. The study by Bouwsema et al involved two groups of subjects; three using hybrid trans-humeral prostheses and three users of myoelectric trans-radial prostheses (8).

In reaching to grasp movements of trans-radial prosthesis users, and regardless of the type of prosthesis control mechanism, compared to the anatomical hand, amputees were found to take longer to complete the task (5, 8). The profile of the prosthetic arm velocity curve is typically a distorted asymmetrical bell-shape whose peak is skewed to the left with a short acceleration phase and lengthy deceleration phase (8). In some instances a velocity profile with a double-peak has been observed (see Figure 2. 14-A).

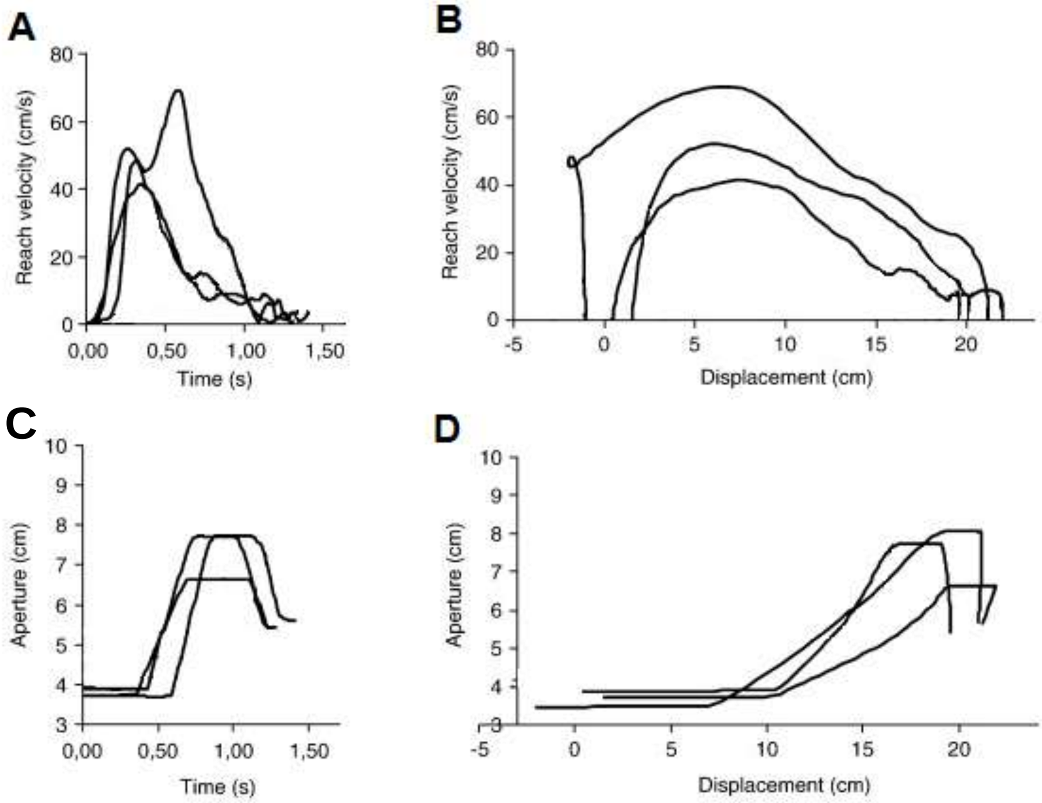


Figure 2. 14: Reach velocity profiles and aperture profiles of the myoelectric trans-radial prosthesis for 3 different subjects for reaching to grasp of a 2 cm diameter object of at a distance of 20 cm. The results are plotted against time in (A) and (C), and against displacement in (B) and (D) (adapted from (8)).

In agreement with Jeannerod's findings in his original work in anatomically intact individuals (27), reach to grasp movement in trans-radial amputees can also be described as consisting of two components; reaching (transport) and grasping (hand aperture) (5). Also consistent with Jeannerod's findings (27) the grasping phase is influenced by the object size (maximum prosthetic hand aperture increases with object size) (5). Finally, peak velocity is also influenced by object distance (8). Notably, unlike the anatomical hand which starts to open almost concurrently with the onset of the reaching movement, the prosthetic hand starts to open later in the reach (8). Bouwsema et al estimated the latency in hand opening in trans-radial myoelectric prosthesis users to be 254 ms comparing with 50 ms in the anatomical hand (27), with the hand not beginning opening until the hand starts to decelerate towards the object (8). When the prosthetic hand aperture reaches its maximum, the hand is typically left open until it almost reaches the object (8). Typical hand aperture profiles, showing the plateau corresponding to maximum hand aperture are shown in Figure 2. 14-C.

Similar behaviours were observed in body powered prosthesis users by Wing and Frazer (5). They also found that the prosthetic hand starts to close nearer to the end of the reach to grasp trajectory than the anatomical hand (about 5.5 mm from the object for the prosthetic hand compared with 17.6 mm for the anatomical hand) (see Figure 2. 15).

Therefore using a prosthesis (myoelectric or body powered) appears to disturb the characteristic temporal relationship between reaching and grasping, described by Jeannerod (27). Notably, the prosthetic hand only starts to close during the long deceleration phase (5, 8), arguably a phase when visual feedback may be available for its control. The major importance of vision in achieving the reach to grasp using a prosthesis was further investigated in the study by Wing and Fraser (5). With the subject blindfolded, they compared reaching to grasp with the prosthesis and the contralateral (anatomical) hand. Out of five attempts with eyes closed only once did the subject complete the task correctly, whereas all attempts were completed correctly using the anatomic arm (5).

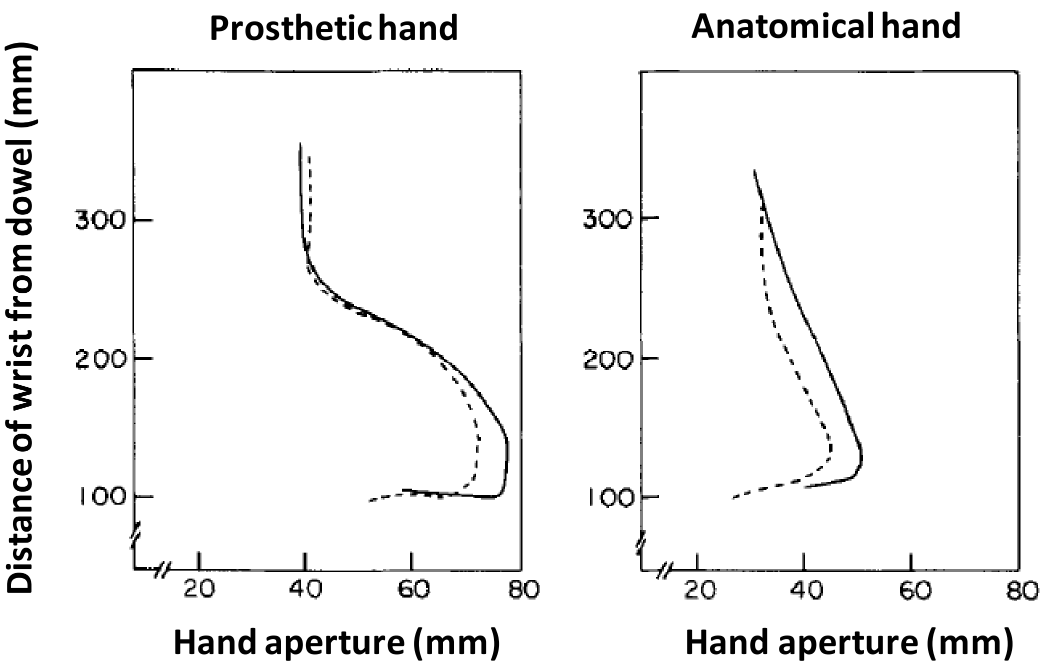


Figure 2. 15: Relationships between distance from object and hand aperture for the 22 mm (solid line) and 12 mm diameter (broken line) dowels (5).

Notably, studies of prostheses and of hand-held tools (such as a grabber) have both reported kinematic characteristics that consistently differ from anatomical hand reach to grasp characteristics. Reaching durations when using a prosthesis (5, 8) or a grabber (64, 66) are longer, show a short acceleration phase and long deceleration phase, and the aperture is characterised by a prominent plateau. The observed increase in both the duration of the deceleration phase and the presence of a prominent plateau in the aperture profile have been interpreted as evidence of a higher reliance on visual feedback (5, 8, 64, 66).

#### *2.10.3. Upper limb movement characteristics in complex manual tasks*

The studies of pointing and single reach to grasp actions only offer limited insight into motor control behaviours in ADLs, which often require complex sequences of reaching, grasping and manipulation. Investigations of upper limb movements during ADL and other complex tasks usually focus on time to complete the tasks (143, 146-148) and/or ‘quality’ of the performance by exploring simple metrics of joint coordination and ranges of motion (ROMs) of different joints (134, 135, 139, 142). Trans-radial myoelectric prostheses (with no powered wrist unit) severely restrict elbow motions (flexion-extension and supination-pronation) due to the socket configuration (70) and in tasks with significant elbow involvement more proximal joints are used to compensate (134, 139).

A myoelectrically controlled powered wrist rotator potentially offers an alternative and seemingly ideal means of compensating for the lack of elbow supination-pronation (81). However, controlling wrist rotation during reaching may not be possible, as prosthetists often assign the same muscle groups to control both the hand and wrist unit and thus the two components can only be controlled sequentially (81).

#### *2.10.4. Characteristics of learning to use prostheses*

Undoubtedly, upper limb prostheses are challenging devices to use and training to acquire such skills is required (149). Early prosthetic training after amputation is believed to enhance the chances of both acceptance and potentially use of the prosthesis (3, 150). It is also reported to reduce the likelihood of amputees developing neglect of the amputated side (103, 150). It is recommended to begin prosthetic training by fitting a prosthesis simulator on the non-amputated side before the stump is ready for prosthetic intervention (137, 150).

Better understanding the process of learning to use a prosthesis can impact, not only on the content of training programmes, but also on design. However, relatively few studies have described the characteristic changes associated with learning to use an upper limb prosthesis. This section will begin with an overview of studies on learning to control the myoelectric signal. This will be followed by sections on learning to use trans-radial prostheses.

#### *2.10.4.1. Learning to control the myoelectric signal*

In myoelectric prostheses, the hand state (opening or closing) is typically controlled via myoelectric activities of one or two muscle groups. The ability to control myoelectric activity in relevant muscles is therefore a key prerequisite of successful myoelectric prosthetic use (104). However, there are relatively few studies on how people learn to control the myoelectric signal.

Dupont and Morin (151) reported on a study in which patients received 10 training sessions, during which they learn to control the myoelectric signal through a software tool. The software presents two mirrored simulated hands on a computer screen; one of which is a target hand whose fingers move between predefined and randomly assigned positions, so the hand randomly opens and closes to different apertures. The other simulated hand is controlled by skin-mounted myoelectric electrodes placed on the wrist flexor and extensor muscles. During training, the subject has to match the hand state of the controlled hand with the target hand. Three levels of difficulty, described by the accuracy required to achieve a match with the target aperture were used in each training session. Performance was evaluated based on a number of metrics, including occurrence of undershooting and overshooting the target, number of successful matches with the target and task completion time.

Performance error in general declined over training for all difficulty levels (although the decline was not significant for some variables). Total control time also showed relatively steady improvement over the course of training for all subjects and for all difficulty levels, although the trend varied between subjects. Comparing total control time between session 1 and 10 showed a significant improvement for all difficulty levels.

In a related study, Bouwsema et al studied anatomically intact subjects during learning to control a myoelectric hand (152). Subjects were assigned to one of three groups, each of which received training with a different approach. The first method involved the use of a software tool similar to the one introduced by Dupont and Morin (151) that simulated the behaviour of a Sensor Hand Speed hand*; in the second method, an actual prosthetic hand (mounted on a table) was used in the training. The third method involved training subjects on reaching, grasping, lifting and releasing a wooden cylinder using a prosthesis mounted on the forearm.

Performance was evaluated before and after three consecutive training sessions. Subjects' performance were evaluated by asking subjects to open and close an actual prosthetic hand (MyoHand VariPlus Speed, programmed to respond as a Sensor Speed hand i.e. provide proportional control over speed) at 3 different speed rates (as fast as possible, preferred speed, and as slow as possible). The outcome measures were the number of myoelectric signal peaks (a measure of smoothness) and peak and mean velocity of the hand during opening and closing the hand.

The three training methods resulted in comparable and statistically significant reductions in the numbers of myoelectric signal peaks and increase in mean and peak velocities of the hand after training. This suggested that the training performance is surprisingly invariant to whether or not the subject uses a physical prosthesis during training and hence virtual approaches offer promise. However, not all subjects showed similar improvements over training. The authors of the study split the subjects into two groups; subjects with high learning capacity (HLC) and others with low learning capacity (LLC). The distinction between the two groups was based on the slope of regression line of the mean hand velocity measured at the three performance speeds after training (i.e. the 'better' subjects should show a greater difference between slowest and fastest velocity and hence steeper slope of the regression line). Differences between groups were found in all parameters. As an example, Figure 2. 16 shows peak velocity post training for the two groups at the three different hand opening rates. The differentiation in learning between groups may have implications for the training procedure and prescription of prostheses.

* http://www.ottobock.com/cps/rde/xchg/ob_com_en/hs.xsl/3652.html

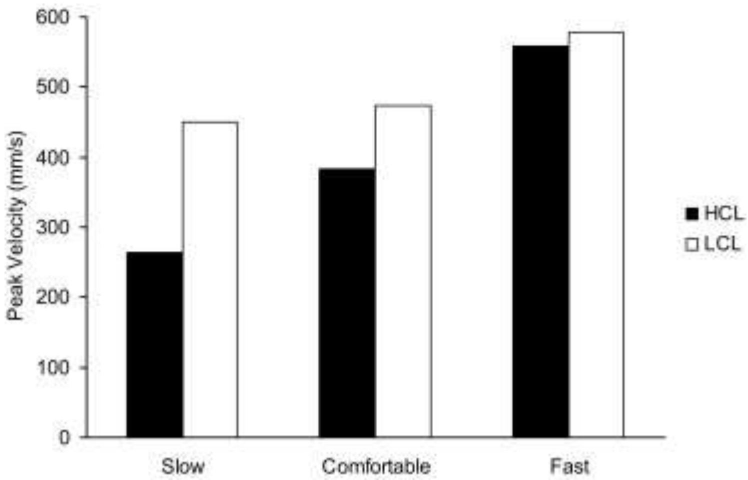


Figure 2. 16: Peak velocity of hand aperture achieved by high and low capacity learners at different performance speed (from (152)).

Based on the observation that individuals vary in their capacity to learn myoelectric control, Takeuchi et al, building on the earlier work of Dupont and Moron (151) proposed an adaptive virtual reality training system that adjusts the tasks' difficulty according to the user's skills (153). In this system, both the prosthetic hand and objects to be grasped are simulated. The relationships between EMG level, hand aperture, object dimension and resultant grip force are modelled and subjects are required to produce an appropriate "grip force" to avoid virtual object slippage or crushing. Task difficulty is characterised by the difference between the maximal and minimal grip force for a given object; the smaller the difference the higher the task difficulty. Prior to training, an algorithm assesses the grip force produced by the amputee to match the task difficulty with the amputee's "Level of skill". During training, the algorithm is used to establish an optimal difference between the maximal and minimal desired forces which is slightly above the amputee's "Level of skill" (the force range that the amputee can achieve before training), termed as "virtual assist".

At the end of the training protocol, the amputee's performance is evaluated to indicate any improvement resulted from the training. This is achieved by measuring the success rate to complete the task without virtual assist.

To examine the advantage of employing a virtual assist in computer software-based prosthetic training, training to use a virtual hand was completed with and without introducing virtual assist in two groups of anatomically intact subjects (153). The effect of training on success rate for both groups was the assessed after training. The success rate in subjects who were provided with a virtual assist was found on average to be higher than in those who were not virtually assisted (153).

#### *2.10.4.2. Learning of pointing tasks*

A small number of studies (7, 133) have explored performance by trans-radial amputees on pointing tasks as an indicator of how well the prosthesis integrates into the internal representation of the arm. As the mass properties of a prosthesis differ from the anatomical arm (7), the CNS has to account for these differences when planning and executing movements.

Schabowsky et al (133) compared the ability of 8 trans-radial amputees with 8 anatomically intact controls to accurately move the handle of a planar robotic manipulandum to three targets in the horizontal plane. Movement was examined under three conditions; baseline (30 repeats of the reaching movement), in the presence of a curl field disturbance to the forces acting on the arm (120 repeats, called the learning stage which was divided into early learning stage (first 35 repeats) and late learning stage (the remaining 85 repeats)), and following its withdrawal (90 repeats, called the learning after-effect stage). The curl field exerted counter-clockwise rotational forces perpendicular to the arm movement, whose magnitude was a function of the instantaneous arm velocity. Introducing a curl field requires adaptation in the internal model of the movement and causes an immediate deterioration in performance which can be indicated from the deviation on the normal straight movement trajectory. As the subject, through the adaptation of his/her internal model of the movement, develops muscle force and timing strategies to compensate for the (predictable) disturbance, hence the movement trajectory returns towards that seen at baseline. Adaptation to the external forces was further assessed in learning after-effect stage by the unexpected removal of the field. To quantify the adaptation, peak error was calculated (the maximum orthogonal distance between a given movement trajectory and the ideal straight trajectory).

In this study, despite the changes to the mechanical properties of the limb following amputation (133), it was found that amputee subjects demonstrated a similar ability to anatomically intact controls to respond to the interfering field in the early learning stage. In the late learning stage, the amputee group showed, a significantly higher peak movement error and variability of error compared with controls. Finally, after completing the learning stage, unexpected removal of the curl field disturbance resulted in no between group differences in any of the kinematic measures. Peak velocity was also the same across the two groups at each stage.

To measure learning rates in both groups, exponential curves were fitted to the movement peak error plotted against reaching attempt number (133). The study found that the ability to learn to adapt movement in amputees seems to occur at the same rate it does in healthy individuals. Finally, the authors investigated the correlation between the performance scores of the amputees on a clinical outcome measure (Nine Hole Peg test) and the peak movement error in the final phase (following removal of the curl field). A high positive correlation was found suggesting that functional performance was related to the ability to adapt to new dynamic situations.

In a second study, the same robotic system was used (but without any active interference from the robot on the forces acting on the arm) to explore the effects of removing visual feedback on the arm (but not the target) in trans-radial prosthesis users (7). Similar to reaching to grasp movement, goal directed pointing is also executed based on a preset plan and arm movement is corrected based on visual and proprioceptive information towards the end of the movement (see review by Sarlegna and Sainburg for further detail (40)). Since visual information cannot be fully replaced by proprioception (33, 40),  by blocking the view of the hand, the subject is forced to largely rely on the kinematic plan (internal model) to reach the target. Comparable pointing accuracy to anatomical intact individuals  under no visual feedback of the hand in amputees would imply incorporation of the prosthetic arm in the internal model used to plan arm movement (7). In this study, movement time, peak velocity, time to peak velocity, peak movement error, and endpoint error and endpoint variability were compared between 10 anatomically intact individuals and 10 amputees (7).

Consistent with Schabowsky's study (133), comparing performance under two visual feedback conditions, under the no visual feedback of arm movement condition, amputees (regardless the differences in their "efficiency" to use the prosthesis as estimated by Nine Hole Peg test) also showed similar decrements in performance on the pointing tasks to the anatomically intact group (7). Both groups showed comparable movement time, peak velocity and similar peak movement error, endpoint error and error variability (7).  The results of both studies suggested that the brain is able to adapt the existing internal models of the anatomical arm to incorporate the prosthetic limb.

#### *2.10.4.3. Learning functional tasks*

Functional use of the prosthesis which involves reach to grasp and manipulating objects requires concurrent control of hand state and arm movement and is arguably considerably more challenging than pointing tasks (154).

A number of researchers have explored how subjects learn to perform functional tasks using a prosthesis (136-138). In these studies, reaction time to initiate the movement, movement time (136-138) and number of attempts in which the task is incorrectly completed have been used as outcome measures (137). Weeks et al (137) examined, in anatomically intact subjects, whether skills acquired from training to use a myoelectric prosthesis simulator are transferable between arms (bilateral or inter-manual transfer of skills). In this study, healthy individuals were assigned into one of three groups. The first group was trained using the non-dominant arm and tested using the dominant arm, the second group was trained using the dominant arm and tested using the non-dominant arm and the third group was a control group that did not receive training. Testing in the control group was completed using the dominant arm for half of the subjects and non-dominant for the second half. Performance was tested before and directly after training (where relevant) and then a day after (a retention test). Testing and training involved completing 3 functional tasks a number of times (30 times for training sessions and 5 times in testing sessions).

Reaction time in both group 1 and 2 declined equally after training, but no changes were observed in the control group (which did not receive any training in between the two testing sessions). This pattern was also seen in the retention test. The improvement in movement time directly after training was similar between the three groups which indicates the absence of immediate skill transfer between limbs. However, movement time in the retention test was evidently shorter in both groups 1 and 2 compared to the control group. The absence of immediate skill transfer agrees with the idea that the neural changes associated with skill acquisition may need some time before they takes place, a phenomenon is known as "consolidation of memory" (137). Reaction time and movement time revealed no effect of the direction of the transfer. Nevertheless, the number of performance mistakes immediately post training differed between groups 1 and 2; group 2 in which the non-dominant arm was trained made more mistakes than group 1 after training. However, in the retention test the difference between groups disappeared.

In general, the results support a high degree of inter-manual transfer of skills in using an upper limb prosthesis. Also, the results indicated that reaction time, movement time and performance mistakes reflect learning to use a prosthesis.

Following on this work, movement time and reaction time were used in two related studies to compare different training programmes (136, 138). It is known that the order in which tasks are presented during training can influence skill acquisition (155). Evidence from studies in anatomically intact individuals suggests that practising in a block order (moving to a second task only when practising the first task is completed) shows faster effects of training, but randomly ordered training results in better retention and transferability (performance on previously unpractised tasks) (155). To what extent this principle applies to upper limb prostheses has been the focus of two recent studies (136, 138). In both studies, anatomically intact subjects fitted with prosthesis simulators were trained to complete three functional tasks and their performance recorded. Subjects were tested twice a day after the training in a retention test where the same three tasks were completed, and then in a transfer test in which performance on 3 new functional tasks were evaluated. The main difference between the two studies is that training was completed over two sessions in Weeks' study (136) whereas in a study by Bouwsema et al training was completed in a single session (138).

Both studies showed that movement time and reaction time improved with training, regardless of the practice order. This improvement was shown to be maintained in both retention and transfer tests (136, 138). Both studies also found that both training approaches resulted in a similar degree of improvement in movement and reaction times in the retention test. In Weeks et al work, subjects who had practised using a random order performed better in the transfer test; this effect of practice order on outcome was not evident in Bouwsema's study.

##### *2.10.4.4. Brain activity changes with learning to use a prosthesis*

As a result of brain plasticity following amputation the cortical somatosensory and motor representation of the amputated part may be "occupied" by other parts of the body (e.g. after trans-radial amputation, the cortical representation of the hand may be invaded by representation of the lip) (156). Regular wear and use of a prosthesis has been shown to reverse such cortical reorganisation (157) and has also been shown to attenuate phantom pain ("painful sensations referred to the absent limb" (158)) (159).

It has been suggested that the characteristic features of reach to grasp in amputees, such as prolonged deceleration phase in reaching velocity profile and appearance of a plateau in the hand grip aperture profile, are a result of a high reliance on vision (5, 8). Recent evidence has revealed that brain activity when first using myoelectric signals to control opening and closing of a simulated hand differ from that observed during anatomical hand opening and closing (160). Controlling the prosthetic hand was associated with strong activity in the ventral premotor cortex, and this activity may reflect the higher visual demands to control myoelectrically controlled hand (160). Nevertheless, while controlling the simulated prosthetic hand, new brain activity emerged that is normally associated with alterations to body schema as a result of learning new skills and tool use (160). For instance, activity in the right posterior parietal cortex was observed, which is usually associated with learning new skills and tool use. The locus of activity of right posterior parietal cortex was also found to be shifted laterally, which is considered to reflect alterations in the body schema. This implies that the brain starts to represent the prosthesis in the body schema probably as an extension of the anatomical arm (160); a behaviour that is widely believed to emerge with tool use (61, 161).

### 2.11. Conclusions and thesis aims

To date, myoelectric prostheses offer a limited replacement for the motor function that is missing in upper limb amputees (2). In the case of trans-radial amputation, most common myoelectric prostheses provide 1 or at most 2 controllable DoFs to compensate for the motor function of the hand and wrist joint. Although devices that provide a higher number of DoF have very recently become commercially available (e.g. i-Limb™ Ultra from Touch Bionics) (90), they are still controlled by at most two independent EMG signals.

In addition to the large number of DoFs in the anatomical hand, sensory feedback from different modalities including vision and proprioception plays an important role in the function of the anatomical hand. Despite research studies to enhance sensory feedback via tactile stimulation (162, 163), none of the commercially available prostheses provide feedback to the user, thus amputees have to rely on vision to monitor the movement (9).

The factors discussed above may provide some of the explanation for the high rate of myoelectric prosthesis rejection (23%) that has been reported recently in adult users (3); a figure that is similar to what was reported more than 20 years ago (3). Prosthesis rejection implies that unilateral amputees would have to rely heavily on the remaining non-amputated arm to perform manual tasks (25, 164).

The poor level of functional restoration offered by current prostheses may explain a number of problems experienced by upper limb amputees. For instance, apart from their amputation, most upper limb amputees are otherwise healthy and of working age. However, a recent study showed 39.7 % of a sample of 307 upper limb amputees were not able to work any longer (165), because of the decline in their functional ability after amputation and insufficient functional return from the prosthesis. Unsurprisingly, in general due to the functional limitations of current prostheses, most amputees who return to work after amputation take part in occupations that are not physically demanding (165-167).

Clinically, the increased work load on the remaining arm may leave unilateral amputees more vulnerable to overuse injuries in the non-amputated arm (168). In fact, a number of studies reported a high incidence of overuse-related injuries in unilateral amputees (169-172). Further, a study has suggested other benefits of wearing and using a myoelectric prosthesis wear, namely a reduction in phantom pain (157), implying that rejection of this type of prosthesis results in a secondary cost.

In order to evaluate upper limb prostheses, a number of tools have been developed over the years. Those can be broadly categorised into two groups: tools for measuring a user's performance on particular functional tasks and questionnaire or interview-based tools to evaluate, for example, users' perceptions of their prosthesis and the extent to which they make use of their prosthesis (4). Useful information regarding prosthetic hand performance and usage can be determined with such evaluation tools and they are well-suited to comparison studies. However, none provide detailed insight into the mechanisms by which a user learns to use their prosthesis and provide very little information with which to inform the design of new prostheses or new training regimes. For example, none of the clinical tools provides insight into the detailed motor control strategies or the attentional demands associated with prosthetic use.

As has demonstrated in this chapter, the motor control literature offers a solid platform from which to explore the process associated with learning to use a prosthesis and the differences in behaviours between healthy and prosthesis functional performance. Despite work in the area of upper limb motor control in prosthesis users carried out in the early 1980s (5, 6), there have been surprisingly few studies describing the characteristic changes in motor behaviour, and no previous work on visuomotor behaviour, associated with learning to use a prosthesis. This is despite the widespread agreement regarding the importance of vision in prosthetic use (6-10). Further, nothing is known about the relationships between visuomotor skill level and more clinically relevant measures, such as usage of the device in everyday life and acceptance of the prosthesis. Studies in these areas may lead to the development of improved outcome measures, improved designs and new training approaches.

This thesis, therefore, aims first to explore the changes to visuomotor behaviours when a myoelectric prosthesis is introduced and over the course of learning to use it. By studying this, the characteristics that change with practice and hence reflect skill acquisition (skill measures) may be identified. In this thesis, skill is defined as "the learned ability to bring about pre-determined results with maximum certainty, often with the minimum outlay of time, of energy, or of both" (173).

Due to the limited number of trans-radial amputees and to avoid burdening newly amputated individuals the core investigation of this thesis was in anatomically intact subjects. However, the results were subsequently validated in a small sample of trans-radial myoelectric prosthesis users. Moreover, in the later investigation in trans-radial myoelectric prosthesis users the relationship between current clinical evaluation tools and proposed measures of skill acquisition was examined.

However, prior to exploring visuomotor characteristics, the following chapter will discuss the approach to characterising gaze behaviour in a manual task. In this chapter, a clinically relevant manual task that will be used to explore visuomotor behaviour changes is identified and finally the development and validation investigation of a coding scheme for gaze data analysis are discussed.

## Chapter 3: Task identification and development and validation of gaze coding scheme

### 3.1. Introduction

Humans have highly refined approaches to acquiring visual information (53). Eye movements are used to direct the high resolution foveal vision into the part of the scene that holds information of relevance to task performance (53). These scene elements, which represent the locations on which overt visual attention is directed during task performance (174), are referred to as area of interests (AOIs) (174).

Eye tracker systems, which monitor eye position and project the estimated direction of gaze into the scene ahead allow for the target of gaze, known as the point of regard, to be recorded (175). This therefore allows the targets of overt visual attention to be inferred (174).

Gaze behaviour characteristics have been explored in subjects performing a number of different upper limb functional tasks, including object transfer (38), hitting and throwing balls in different sports (176, 177), making a cup of tea (49) making sandwiches (51), playing musical instruments (178) and hand-washing (48). The findings from these studies suggest a number of features of how gaze is related to motor planning (179). First, the gaze fixations are intimately linked to the specific requirements of the task; gaze fixations are predominantly on objects/locations relevant to the task while irrelevant objects/locations to the task are rarely fixated. Therefore, gaze fixation sequences exhibited during the performance of a particular familiar multi-stage task are often stereotypical, with similar behaviours exhibited across different subjects (180). Furthermore, gaze fixations were also found to be temporally coupled with the actions of the task; where gaze fixations tend to hit the action-related parts of the scene before the onset of the intended actions (“look-ahead fixations”) (48, 50). Finally, gaze most often leaves the objects being acted upon before the action is completed (49).

Evidence suggests these task-specific stereotypical gaze sequences emerge with practice (180). For instance, using a novel mouse-like tool to hit a series of sequentially displayed targets on a screen**,** subjects changed their gaze behaviour from initially pursuing the cursor with occasional fixations of the target to leading the cursor movement and fixating of the intended target (62). Studies have compared gaze behaviour of novices and experts during the performance of manual tasks in a number of different domains (68, 181-183). Law et al (68) for instance, found that expert users of the laparoscopic tools fixate their gaze exclusively at the intended target while reaching to it, whereas novices’ gaze was initially focused on the tool itself while approaching the target, before fixating at the target. When potentially relevant visual information is distributed across a complex scene, such as the cockpit display panel during flight landing, expert (pilots) showed more stereotypical gaze scanpaths compared to novices (181), suggesting they have learnt where the most relevant visual information is likely to be found. In studies of sporting activities, such as baseball, cricket tennis and table tennis, clear differences in gaze behaviour between novices and experts have been reported (176, 177). Experts in general exhibited gaze behaviours that indicate their higher ability to anticipate actions and better ability to process information. Expert batsmen in cricket, for instance, tend to fixate earlier than novices at the anticipated location where the ball will bounce (177), a finding also observed in tennis (176). Additionally, the fixation sequences of experts are found to be associated with relevant scene areas and are less variable, which could be argued to reflect more efficient allocation of attentional resources (176). This for instance was observed in expert tennis players who generate fewer and longer fixations at the shoulder or trunk of the opponent to anticipate the ball direction, whereas novices fixated their gaze more frequently at distal and less relevant areas, such as the racket and ball-racket contact area (176).

In previous work, in order to quantify the gaze behaviour during manual performance, researchers generally considered the visual scene to consist of a number of AOIs and observed how gaze moves between these AOIs and how long the gaze fixation lasts on each of the AOIs while performing the tasks (38, 48-51, 176, 184, 185). Therefore, interpretation of the data was constrained by the definition of the AOIs. However, in most of the previous studies concerned with manual performance (38, 48-51), AOIs have rarely been explicitly defined before data coding, and most often conclusions have been drawn based on descriptive AOIs, rather than well defined and pre-coded AOIs. Typically, AOIs were considered to be the objects and/or targets displayed in the visual scene (38, 48-52, 176, 184, 185). For example, when Land and team investigated gaze behaviour during the process of making a cup of tea (49), and also when Hayhoe explored gaze behaviour while making sandwiches (51), each object presented in the scene ahead was mostly implicitly coded as an AOI (e.g. knife, jar, kettle, sugar caddy), and hence fixations were named after the object at which the fixation takes place. Occasionally, AOIs representing one part of an object were considered (e.g. fixation at teapot spout (but not kettle spout or handle in Land et al (49) (see figure 2 and 3 in (49)), but the boundaries defining these areas within objects were not reported. Therefore, it seems that in earlier work, the AOIs evolved while coding the gaze data and their boundaries were to a great extent defined based on the rater’s opinion. This absence of clearly defined schemes is likely to render the process of coding gaze data (assigning gaze location to AOI) open to the personal interpretation of the rater(s).

Studies by Williams and team (see for examples (176, 185)) perhaps are notable exceptions. In their studies, AOIs were defined before coding. For example, in order to study the gaze behaviours of expert and novice tennis players Williams et al, divided the whole scene ahead into 8 AOIs, including: head–shoulder, trunk–hips, arm–hand, leg–foot, racket, ball, and racket–ball contact areas, in addition to an “unclassified area” which accounted for the remaining uncoded part of the scene (176).

The majority of earlier work concerned with performance of manual tasks (38, 48-51) were based on the assumption that the key descriptors of a fixation are its timing and on which object in the scene it is focused. The exact location of the fixation on the object is rarely detailed. However, Johansson et al (38) studied gaze behaviour during reaching to grasp a bar from one end with the intention to hit a target with the other end passing, in some trials, around an obstacle. Johansson showed that gaze, during task performance, does not hit the object in an arbitrary location, but rather hits certain landmarks (38). Those landmarks appear to be selected based on their importance to the performance of the task, for instance, in this study, when object grasping was intended, fixations were most often exclusively fixating at the grasping site of the bar (38). In line with this finding, in a study by Rothkopf et al, (186) they observed that if an object is used to perform two different tasks, the localisation of fixations on the object may change. That is, subjects made fixations at the centre of an object when they intended to pick it up and around the edge when they wanted to avoid it  (186).

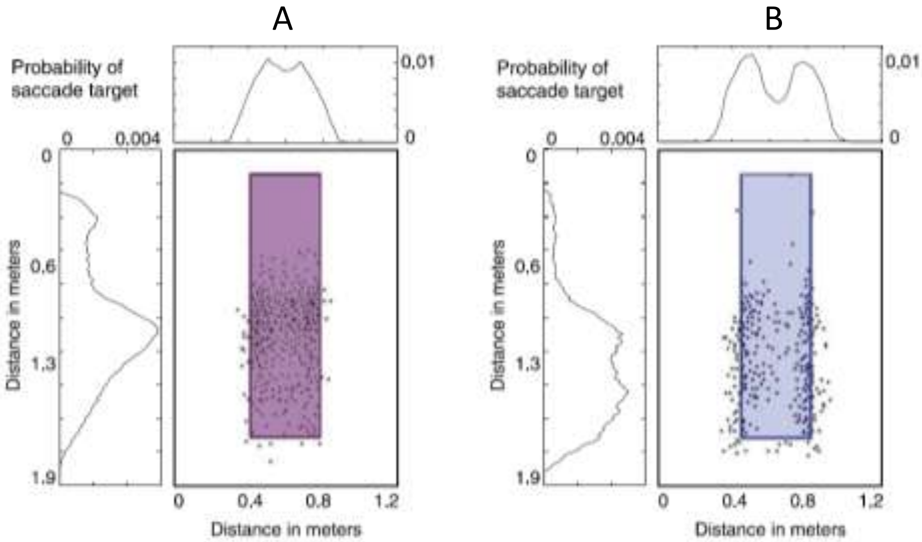


Figure 3. 1: Horizontal and vertical marginal distributions of gaze fixations on the objects in a study by Rothkopf et al (186). (A) shows the fixation distributions associated with "pickup" the object and B shown the distributions resulted when the object was to be avoided. The distributions were obtained using data from all 19 subjects (from (186)).

In related works, gaze fixation was found to hit the object's centre of the gravity (COG) when the task was simply to look at the object. When the intention was to reach and grasp the object, in addition to the COG, gaze was also fixated near the index finger-object contact area, near to the top of the object (see for example Figure 3. 2) (187, 188). These findings suggest that describing gaze behaviour in terms of fixations on objects in the scene as single units may be losing useful information.

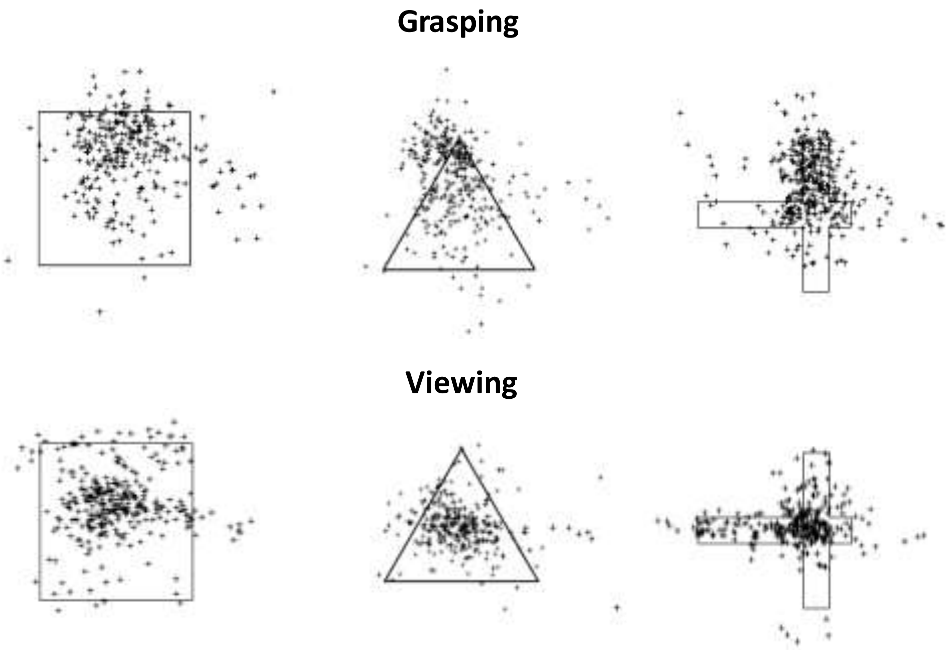


Figure 3. 2: The distributions of gaze fixations made by all participants associated with grasping and viewing objects in a study by Brouwer et al (187).

Interestingly, localizations of gaze fixations on an object have been shown to be influenced, not only by the intended action, but also by the subsequent action(s). For instance, in the study by Johansson et al (38) during reaching, gaze was first fixated on the area of the bar where the thumb and index fingers were subsequently to grasp the object, followed by a fixation at the distal end of the bar, anticipating its movement around an obstacle. These observations suggest that the gaze fixations within an object's boundaries have functional relevance that should be accounted for when coding gaze data.

Further, as some of the tasks reported on in the literature are complex; involving objects moving within the scene and interacting with other objects (49, 51), the potential for ambiguity in coding is likely to arise.

Surprisingly, despite the obvious difficulties with gaze coding complex sequences of actions without a clearly defined coding scheme, to the author's knowledge, the reliability of gaze coding has never previously been examined. For instance, to the author's knowledge, gaze data have never been coded twice by two independent raters to examine the agreement between raters.

Therefore, this chapter describes the identification of a suitable task for use in the main studies presented in later chapters. An experiment in which gaze data were collected from a small number of participants performing the task is then described. The aim of the study was to develop and investigate the reliability of an objective gaze coding scheme for the task. Firstly, Area of interests (AOIs) in the scene ahead are strictly defined based on a functional interpretation; hence an AOI may be an area in the scene object, or part of it, or an area of interaction between areas/objects based on its function in task completion. A method is then proposed for dealing with potential ambiguity in AOI interpretation, followed by a description of a preliminary coding scheme. Finally, an inter-rater reliability study demonstrating the reliability of the proposed coding scheme is reported.

## 3.2. Methods

### *3.2.1. Task selection*

In order to explore gaze behaviour when using a prosthesis, a well-defined task is required. The task will be used in subsequent chapters to explore gaze behaviour both when performing the task with the prosthesis and with the anatomic hand.

As highlighted in Chapter 2, in studies comparing anatomical with prosthetic performance, few clear difference were found between movement of the arm in anatomically intact subjects and amputees during pointing tasks (7, 133). Amputee users of myoelectric prostheses were found to exhibit more distinct differences from normal in movement kinematics when the tasks involved active use of the hand (5, 8). Some of these differences appear to be consistent with the long-held belief that amputees rely more heavily on visual feedback when performing reach to grasp tasks (e.g. see Section 2.10.2, Chapter 2). Therefore, it is sensible for this work to include a task that requires reaching to grasp.

Additionally, from work on gaze behaviour during multistage task performance (consisting of a number of sequential actions), gaze fixates at the part of the scene that holds the necessary information for the action before the initiation of the action (51). This suggests that actions are anticipated and planned ahead in time and that actions are often finished off without direct visual feedback (49, 50).

Since prosthesis use may be associated with high reliance on visual feedback (5, 8), the key role of vision in planning actions in multistage tasks may be affected when the prosthesis is used. This aspect can be investigated through studying performance on a multistage task. However, the task should be challenging to the subjects and require their visual attention, so that when overt attention is mainly devoted to the prosthetic movement, the task performance may deteriorate. The task should also be well-practiced in everyday situations (i.e. ADLs); so changes in kinematic and gaze behaviour could be sensibly attributed to the prosthetic intervention rather than to gaining familiarity with the task itself.

Preferably, the task should include relatively large objects. This would allow the potential to define AOIs that are large enough to be relatively insensitive to small errors in gaze fixation. Also if the object to be grasped is significantly larger than the hand, changes in gaze based on grasp location, such as those shown in the study of Johansson et al (38) would be apparent. However, as the task will be used to study the movement kinematics as well, very large objects may occlude the reflective markers (which will be attached to the body segments, as described in Chapter 4). Finally, and most importantly, the task must be achievable using a prosthesis.

It was decided to select a task from a clinical test of upper limb prosthesis function. As described in Chapter 2, the Southampton Hand Assessment Procedure (SHAP) is a well accepted tool for this purpose (25). SHAP comprises a list of manual tasks that are designed to be achievable using a prosthesis. Of the 26 tasks of SHAP, 12 are abstract tasks, which aim specifically to evaluate the prehension in isolation of the complexity of task requirements in real life situation. These tasks were therefore excluded. The remaining 14 tasks are all ADLs. Of these ADLs, pouring water from a carton and pouring water from a jug seemed to meet all of the selection criteria (see Table 3. 1). The jug was, however, difficult to acquire using the prosthetic hand due to its handle's shape (a slippery narrow handle with not enough room to allow the fingers close around it) and was found to be very reflective which would interfere with the process of marker data collection. Therefore, pouring water from a carton into a glass was selected.

| ADL | Multistage | Well-practiced | Challenging | Involving large object |
|---|---|---|---|---|
| Pick up coins | √ | √ | √ | × |
| Button board | √ | √ | √ | × |
| Cutting | √ | √ | × | × |
| Page turning | √ | √ | × | √ |
| Jar lid undoing | √ | √ | × | × |
| Pouring from jug (100 ml) | √ | √ | √ | √ |
| Pouring from carton (200 ml) | √ | √ | √ | √ |
| Large heavy object (full jar) | √ | √ | × | √ |
| Large light object (empty tin) | √ | √ | × | √ |
| Lift tray | √ | √ | × | √ |
| Rotate key | √ | √ | × | × |
| Open/close zip | √ | √ | √ | × |
| Rotate screw | √ | √ | √ | × |
| Door handle | √ | √ | × | × |

Table 3. 1: SHAP ADLs and the inclusion criteria. (√) indicates that the task meets the corresponding criterion and (×) that it does not.

In summary, the carton pouring task is, first of all, a multistage task and presumably challenging when performed with the prosthesis especially because the carton is squeezable and thus subjects have to apply appropriate force to hold it. In addition, the task has a cost (water spillage) associated with poor performance thus encouraging attentional engagement.

Nevertheless, it is normally still well-practiced in real life situations. The task also involves reaching to grasp a relatively large object, the carton, which would not be totally obscured by the hand, but equally will not obscure camera visibility of the hand. The suitability of the task was demonstrated in the pilot work (see Appendix L).

In order to develop and investigate the reliability of a gaze coding scheme, a study was carried out, as described in the following sections.

### 3.2.2. Subjects

Following ethical approval from the University of Salford's Research Ethics Committee (Ref # REPN09/174), 2 right-handed anatomically intact male subjects (28 and 30 years) were recruited for this study. Both subjects did not wear glasses or contact lenses at the time of the study and considered themselves to have normal vision acuity. Prior to admission to the study, both subjects signed an informed consent form.

### 3.2.3. Data collection

Gaze data collection was completed over two separate testing sessions approximately 3 days apart. In the first session, the task was performed using the anatomical arm; in the second session data were collected while using a myoelectric prosthesis simulator, fitted over the same anatomical arm.

#### *3.2.3.1.* The myoelectric prosthesis simulator

The myoelectric prosthesis simulator (Figure 3. 3) comprises a custom-made socket which extended over the intact forearm and hand and was designed to minimise overall length. A myoelectric hand ("Select" Myo electric hand, RSLSteeper, Leeds, UK), size 8 ¼″ was fitted to the socket. For control, an on/off two-site two-state control scheme was used. The hand opened/closed at a pre-set velocity when the rectified, smoothed value of the myoelectric signal taken from electrodes on the extensor/flexor muscle respectively exceeded a clinician defined threshold. The prosthesis was provided with a passive frictional wrist unit so subjects could rotate the passive coupling between the socket and hand using their contra-lateral hand prior to performing a task.

At the time of the experiment, only a left prosthetic hand was available and therefore it was possible to customise a prosthesis for the left side only. Therefore, the task was performed using the left hand.

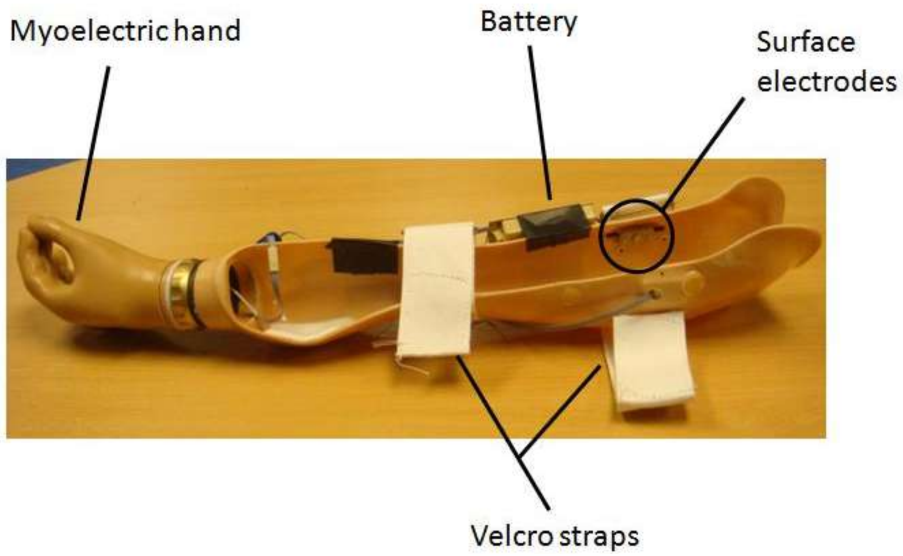


Figure 3. 3: Myoelectric prosthesis simulator.

### *3.2.4. Experimental setup*

Subjects were seated on a chair with their back resting against the chair's upright back and the midline of the torso aligned approximately with the midline of a 60 x 60 x 68 cm table. The upper arms were at the side of the body, elbows in a 90° flexed position and both hands resting comfortably on the table[†]. The locations of the hands when resting on the table (Hand Resting Positions (HRPs)) were marked on paper to ensure a similar arm posture and hand location at the start and end of each trial, throughout testing. The carton (9.5 x 7 x 23 cm), filled with 200 ml of water, was placed within a comfortable reach from the left hand's start point, such that the subject was not required to learn to perform the task (approx 30 cm from the proximal edge of the table in front of the subject's left hand). The carton was oriented with its posterior wall rotated 60° clockwise relative to the proximal border of the table to allow easy access to the carton during gasping. A glass, into which the water was to be poured, was placed to the right to the carton (35 cm from the right boarder and 30 cm from the proximal boarder of the table). A point "gaze reference point" (GRP) was marked in the centre of the table (approximately 10 cm from the distal edge of the table). This point was a visual start and end point for all subjects throughout the test to ensure that subjects do not fixate the carton prior to task onset. A plan view of the experimental setup is shown in Figure 3. 4.

[†] Note: The resting position of the anatomical hand included the hand being flat with the palm facing downwards. The prosthetic hand was pre-oriented in the mid-position, with the palm aligned approximately in the vertical plane.

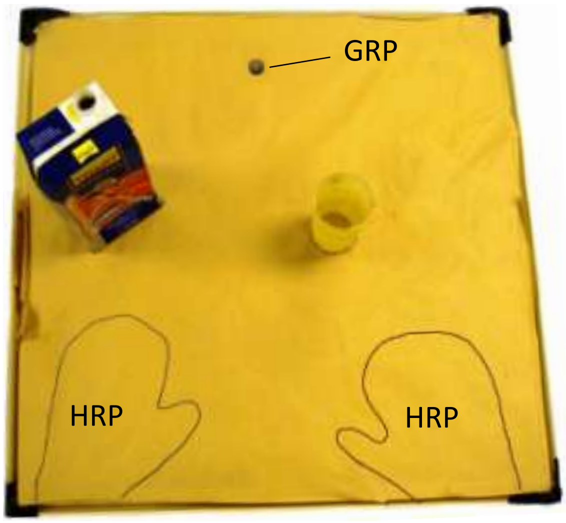

Figure 3. 4: Experimental setup (top view).

### *3.2.5. Task performance*

From the starting position described above, the subject was first instructed to focus on the GRP and then instructed to begin the task. The manual task involved reaching with the left hand for the juice carton picking it up, and then pouring all of the water from the carton to a glass. Finally, the subject was required to place the carton back to its starting point, release the carton and return the hand to its starting point. After that, the subject was instructed to return their gaze to the GRP. During task performance, subjects were allowed to move their eyes freely. Furthermore, head movements during task performance were unconstrained. Subjects were also instructed to perform the task at a self-selected speed.

When the prosthesis was used, the table was moved forward relative to the chair to accommodate the extra-length of the prosthesis. In each testing session, subjects completed the manual task as described above 12 times. After each trial of task completion, the carton was refilled with the same amount of water (200 ml).

Subjects were instructed to repeat the ADL task 12 times in each session and the first 5 trials which showed good visibility of gaze cursor were used for analysis in this Chapter.

### *3.2.6. Instrumentation for gaze data capturing and initial processing*

Gaze data were captured using head mounted iView X™ HED 2 (SenseMotoric Instruments GmbH, Tellow, Germany) eye-tracking system. The system, as shown in Figure 3. 5, comprises two video cameras, one of which captures the image of the eyes (eye camera) at a sampling rate of 50 Hz, and the second captures the scene ahead at a sampling rate of 25 Hz (scene camera). To direct the eye image to the eye camera, a translucent plastic “mirror” (3 in Figure 3. 5) combined with a source of infrared light (4 in Figure 3. 5) is used. The system defines the gaze position with an accuracy of between 0.5° - 1° (189). Since the sampling frequency of the eye camera is less than 200 Hz, it is considered a low speed system, which primarily detects gaze fixations and blinks, based upon which saccades can then be estimated (190).

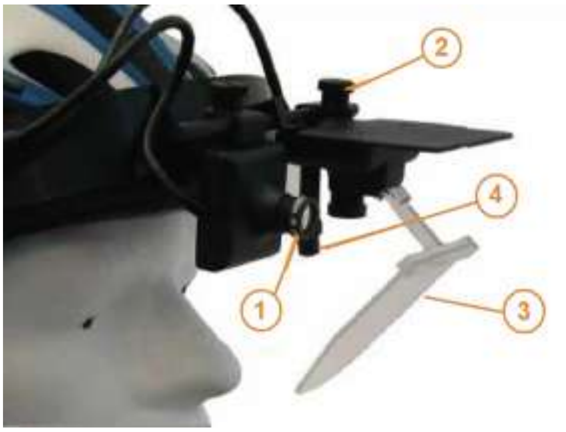


Figure 3. 5: iView X HED 2: the scene (1) and eye (2) cameras, the mirror (3) and the infra-red light source (4) used to illuminate the eye (adapted from (190)).

In order to setup the eye tracker, the researcher securely fitted the helmet-mounted cameras to the subject’s head while he/she was sitting at the table on which the experiment was conducted. The researcher then adjusted the view of each camera separately to display the subject’s eye and the experimental workspace clearly.

Prior to gaze data capturing, a calibration process mapped eye orientation to point of regard in the scene ahead. For calibration, the subject was instructed to fixate at one of five calibration points located centrally in the area of the visual field in which task elements were to be contained. The system recorded the position of the pupil and associated it with the position of the calibration points. This allowed the system then to map each possible pupil position with a point in the scene ahead.

In the iView X™ HED 2, the video data captured by both cameras are transferred into iView X™ workstation (a laptop running iView X™ software). The videos are then displayed and processed in real time in iView X™ software to calculate the point of regard. The iView X™ software comprises a built-in image processing algorithm which detects the pupil and the corneal reflection and defines the position (in pixels) of their centres relative to a reference point in the eye video in real time. The pupil's location changes with the movement of the eye relative to the camera. Based on data gathered in a calibration process, the pupil's location is then used by another algorithm to project the gaze position onto the displayed scene. The resulting gaze data comprises a video file for the scene with a gaze cursor representing the eye position relative to the scene and a numerical data file for the position of the gaze cursor (in pixels) relative to a reference point in the scene video.

After decoding the eye position relative to the scene camera, further processing is required to discriminate non-fixation events (including saccades, blinks and missing data) from fixation periods. BeGaze behavioural and gaze analysis software (BeGaze™ 2.3, SenseMotoric Instruments GmbH, Tellow, Germany) was used for this purpose. It applies a dispersion-based algorithm (see (191) for further detail on the algorithm) to detect the fixation periods from iView gaze data. The major processing steps completed to project the gaze cursor into the scene video in iView and steps to define gaze events in BeGaze are presented in Figure 3. 6.

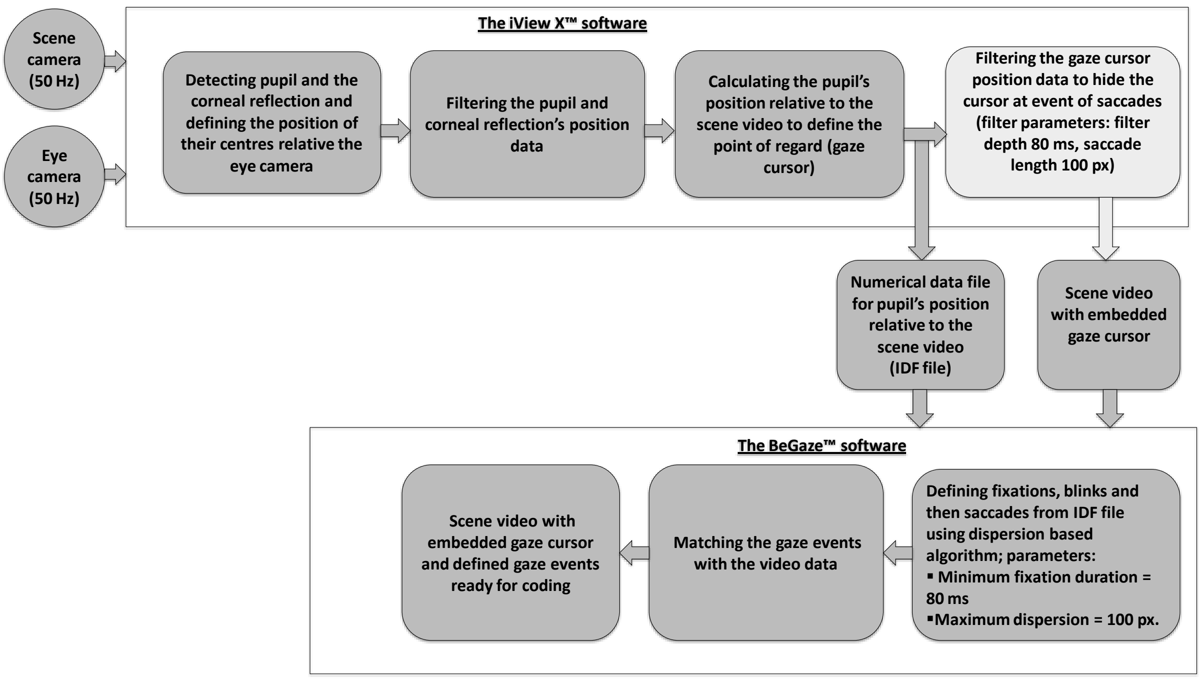


Figure 3. 6: The processing in iView and BeGaze software used to calculate gaze cursor position ready for coding.

## 3.3. Development of the coding scheme

### *3.3.1. Description of AOIs*

For gaze analysis, the scene ahead is typically subdivided into a number of AOIs. Unlike coding gaze data of static images, manual task performance involves a dynamic scene where both the shape and relative position of AOIs in the scene may change throughout the task performance. As discussed in the introduction, a detailed coding scheme is required to reduce the potential for bias and to account for some of the complexities inherent in a multi-stage, multi object task. The following section discusses the process of development of this coding scheme. A detailed description of the AOIs is provided in Appendix A.

As discussed in the Introduction, most researchers who have studied functional tasks considered objects in the scene ahead as AOIs (kettle (49), knife, jar (192)). This approach is a useful starting point. Therefore, initially each of the 3 objects in the visual scene were considered as an AOI: Hand (H), Carton and Glass (GL). In addition, the carton location on the table (Carton End-Point (CEP)) was defined as a separate AOI. Object boundaries were used to define these AOIs. In addition, 4 further AOIs were defined that were not part of an object, but functionally related to the nearby object or following the object: “Following Hand” (FH), “Following Carton” (FC), “Above Carton” (AC) and “Above Glass” (AGL). Following inspection of pilot data (193), it was seen that the fixation occurred at particular sites or “landmarks” on the objects, as Johansson et al found in their study (38). Therefore, it was proposed to divide the area that an object occupies into a number of AOIs. These AOIs were defined based on the assumption that each AOI should have some potential functional relevance, or serve as an isolator that encloses the remaining functionally irrelevant part of the object/scene. Figure 3. 7 shows the coding scheme.

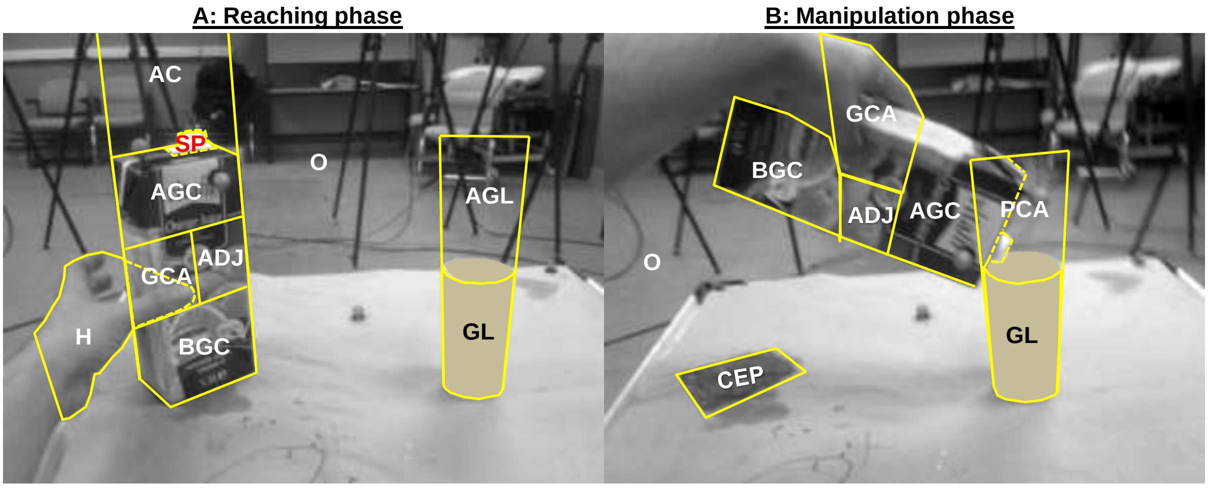


Figure 3. 7: The areas of interest (AOIs). H: Hand, GCA: Grasping Critical Area, ADJ: Adjecent to GCA, BGC: Below GCA, AGC: Above GCA, AC: Above Carton, SP: Spout, GL: Glass, AGL: Above Glass, CEP: Carton End-Point, PCA: Pouring Crticial Area, FH: Following Hand (not shown), FC: Following Carton (not shown), and O: Other.

Of the objects presented in the scene, it appeared that only the carton needed further subdividing into smaller AOIs, as a result of its interaction with the hand. When the hand contacts the carton, 4 AOIs emerge; the first AOI represents the hand-carton interface, referred to as the Grasping Critical Area (GCA). The GCA is surrounded by 3 AOIs; Above GCA (AGC), Below GCA (BGC), and Adjacent to GCA (ADJ). The area above the GCA also consists of a specialised part of the carton which is specifically concerned with pouring, the Spout (SP). Therefore, the spout was considered as a separate AOI. The possible functional meanings of the carton-related AOIs are listed in Table 3. 2.

| **AOIs** | **Functional meaning(s)** |
|---|---|
| Grasping Critical Area (GCA) | Mostly guiding grasping. |
| Above GCA (AGC) | Locating the carton, planning transferring the carton to glass, and guiding the carton/checking the desired orientation of the carton. |
| Below GCA (BGC) | Guiding the carton to, and checking, the endpoint location on the table |
| Adjacent to GCA (ADJ) | Isolator (no obvious function). |
| Following Carton (FC) | Guiding the carton to the glass. |
| Spout (SP) | Locating the carton, planning transferring the carton/water to the glass, checking the desired orientation of the carton and checking the pouring action. |
| Above Carton (AC) | Locating the carton location and planning transferring the carton to the glass. |
| Pouring Critical Area (PCA) | Checking the pouring action. |

Table 3. 2: The assumed functional meaning of the carton-related AOIs.

The GCA was suggested to come into existence from the onset of the task and to last the entire length of the task. It was proposed to define it, prior to coding, by playing the gaze video to estimate the location on the carton of the hand during initial grasping. By definition, the location and size of the GCA are subject to between-trial and between-subject variations.

As discussed above, AOIs may overlap during performance of the task, and two instances were identified:

1. When the hand is in the vicinity of the GCA and about to acquire the carton fixation at the interaction could be assumed to be to check the grip, a function assigned to GCA. Therefore, when the two AOIs (H and GCA) overlapped, the frame was coded as GCA, not H. After the grasp had been established, H was incorporated into the GCA. This meant that H, by definition, did not exist in the manipulation phase (See Figure 3. 7-B);

2. When SP and/or AGC are in the vicinity of the AGL during the attempt to pour water, fixation at the interaction could be taken to be for the purpose of monitoring the pouring process (a new function). Therefore, when SP and/or AGC intersect with AGL, a new AOI replaces AGL, defined as the Pouring Critical Area (PCA). PCA is replaced by AGL once all parts of the carton are outside the AGL area - typically, this occurs once pouring has been completed.

In addition to these AOIs, the remaining part of the scene was further defined as “Other” AOI (O); thus allowing any fixation in the scene to be unambiguously coded. Additionally, a category called “Missing data” (MD) was defined, which covered saccades, blinks and periods when for any other unknown reason the eye location was lost.

### *3.3.2. Dimensionality discrepancy*

In the eye tracker, the gaze position in the actual 3D scene is projected onto a 2D video, hence no information about the depth is provided. This discrepancy in the dimensionality might make also the gaze position open to misinterpretation. For instance, if two AOIs overlap with each other in the line of sight, a common occurrence in manual tasks, the gaze cursor would be projected on to the object that is closer to the subject.

Although mostly it is possible to judge where the gaze is fixated, there is ambiguity in some cases. For example, in cases where gaze is focused on one object and, a second object is moved to partly obscure vision of the first object, it is difficult to judge whether the subject is taking information from the near or far object. Judgment is then open to the subjective interpretation of the rater. To avoid this problem, a confusion matrix (Appendix A) was introduced which showed all the possible overlapping between the AOIs, and in each case, one of the overlapped AOIs was prioritized.

## 3.4. Coding scheme reliability and comparison with a simple coding scheme

Despite the efforts to reduce the subjectivity in gaze coding, undoubtedly raters would vary in their decisions. For instance, the rater has to decide which AOIs to consider when the gaze is fixating marginally between two or more AOIs. This observation highlighted the need for a reliability assessment of the coding approach.

Two raters (M and R) were therefore invited to separately code the gaze data of interest. Prior to coding, the raters met to discuss the coding scheme and to explore some pretesting coding examples. In these meetings, the raters sought to reach consensus on the coding rules. These meetings did not involve coding any of the trials included in the reliability study described here, nor did they involve discussion of the expected outcomes of the study.

For the purpose of the reliability investigation, 20 trials were assigned for coding; 5 trials from each subject from each testing session. Each rater was then invited to firstly define the onset and the end of the task based on the hand movement and then to code the video. The onset of the task was defined as the frame when the hand was first observed to start moving towards the target; the end of the task was defined to be when the carton was in contact with the table and the fingers first lost contact with the carton following its placement back on the reference point. Raters were instructed to code firmly in accordance with the rules of the coding scheme.

As a final check to demonstrate the value of using the more complex coding scheme compared to the simple, object-based coding approach used by Land et al (49) and Hayhoe et al (51), the gaze duration for the two testing conditions were compared; first, when coding objects in the scene ahead only, and when coding using the full proposed coding scheme. The value was judged qualitatively based on the extent of differences between gaze duration at AOIs seen in task performance with the prosthesis and the anatomical hand.

### *3.4.1. Data analysis*

As described above, once the gaze data were exported into the BeGaze software, a built-in algorithm automatically identifies gaze events (fixation, blinks and missing data, then saccades) based on the predefined parameters. Gaze events then presented in parallel with video data of the scene with an embedded gaze cursor. Therefore, the rater was able to go through gaze data frame by frame to define the periods of fixation, blinks, missing data and saccades and to identify which AOIs were fixated over which periods. In the coding scheme, blinks, saccades and missing data were all labelled as “Missing data” (MD).

To present the gaze sequence, gaze data were first normalised by dividing each gaze event’s duration by the task duration. Then gaze sequence was presented in stacked bars in which each coloured portion corresponds to the percentage of fixation at a single AOI (black portions represent MD).

To compare the coding agreement between the two raters, the sum of gaze duration at each AOI was calculated (gaze duration is the sum of all fixation durations (194)).

Finally, in order to confirm that the proposed detailed coding scheme adds value over a simple coding scheme, gaze data coded using the most complex scheme was aggregated into a simple coding scheme. The scheme aggregated all AOIs related to the carton and any AOI out of the objects was aggregated with “Other”. This scheme therefore only showed the gaze duration at the objects (carton and glass) and the hand.

### *3.4.2. Statistical analyses*

All Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows version 16.0, IBM SPSS Inc, Chicago, USA).

Before conducting any statistical analysis, the normality of distribution of the explored data was firstly checked using the Kolmogorov-Smirnov test. When the assumption of the normality was violated (reported p-value less than 0.05) data were transformed, as appropriate.

As the main interest of the reliability investigation is to explore the agreement of the raters to code gaze regardless of the testing condition, all trials of both subjects were treated as one sample that was rated by two independent raters.

To explore whether the difference in estimation of task duration between the two raters is statistically significant, a paired t-test was conducted in which task duration values for the 20 (5 trials x 2 subjects x 2 conditions) coded trials were compared between raters.

To examine the agreement between the two raters on gaze coding, the total gaze duration at AOIs were compared using the Intra-Class Correlation coefficient (ICC). The ICC aims to examine the relationship between two measures of the same action using the same scale. Therefore, it is commonly used to assess the consistency of different raters in describing the same event. ICC = 1 indicates a full agreement and 0 indicates no agreement between raters. Because the two raters were not selectively assigned and since they coded the same data set, two-way random ICC was used.

In addition to ICC Cronbach's alpha coefficient is also reported. A Cronbach's alpha value closer to 1 indicates higher internal consistency.

### *3.4.3. Results*

Paired t-test (after log transform of the data) revealed no significant difference between the task duration reported by rater M (mean = 14.4, SD= 4.7) and rater R (mean =14.6, SD= 5); (t= -.64, p > .05).

Figure 3. 8 and Figure 3. 9 show trial by trial gaze sequence as coded by each rater for subject 1 and subject 2 respectively. Although raters disagreed on some AOIs and with some variation in gaze duration, generally similar gaze sequences were produced by the two raters. Figure 3. 10 illustrates the total gaze duration at each AOI for anatomical hand and prosthetic hand at each AOI as coded by the two raters. The raters appeared to show high absolute agreement for the total fixation duration for each AOI (2-way random ICC = 0.975, $p < .05$) with high internal consistency (Cronbach's alpha coefficient = 0.987).

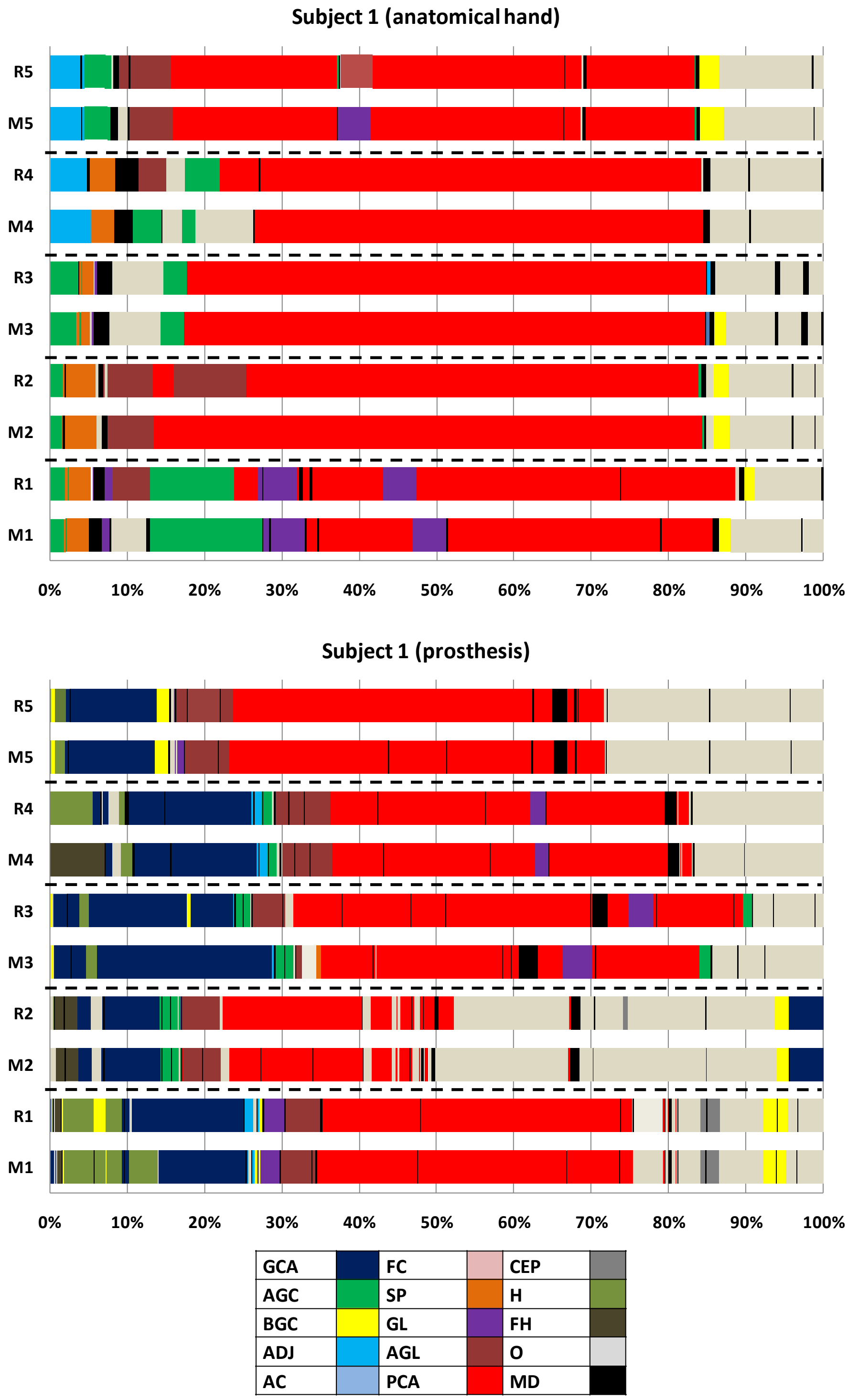


Figure 3. 8: Gaze sequence resulting from the coding of the two raters for gaze data of subject 1 under the two testing conditions. In this figure, the vertical axis represents the rater and trial number (e.g. M1 represents the results of rater M, trial 1), the horizontal axis represents the task duration, normalised to 100%. To facilitate comparison between the coding results of the two raters, the coding results of each trial by the two raters are presented on top of each other (e.g. M1 followed by R1). The fixation sequence in a given trial is presented in a stacked bar in which each coloured segment denotes a gaze fixation at a particular AOI, and the length of each segment corresponds to the duration of the fixation at the AOI.

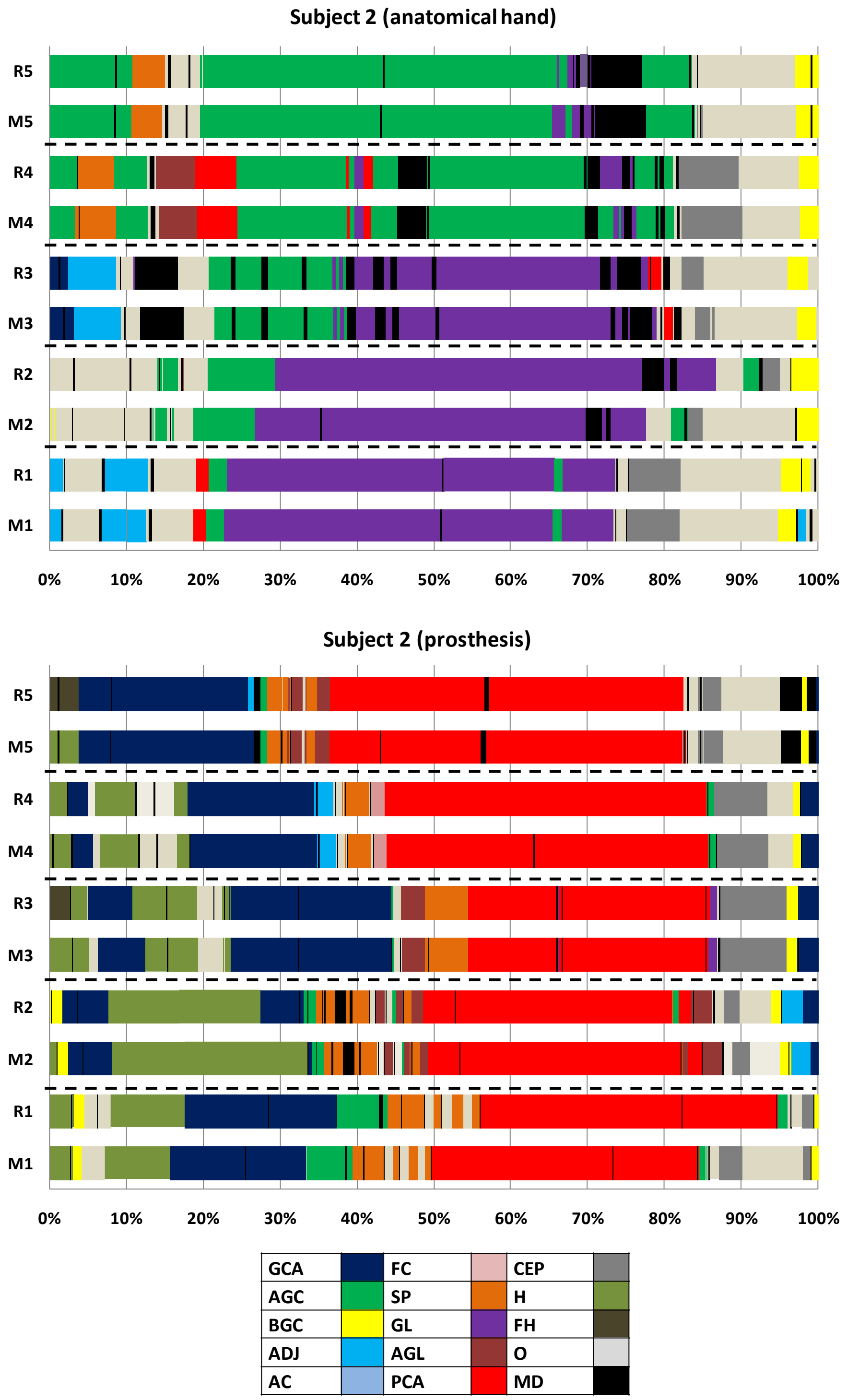


Figure 3. 9: Gaze sequence resulting from the coding of the two raters for gaze data of subject 2 under the two testing conditions. In this figure, the vertical axis represents the rater and trial number (e.g. M1 represents the results of rater M, trial 1), the horizontal axis represents the task duration, normalised to 100%. To facilitate comparison between the coding results of the two raters, the coding results of each trial by the two raters are presented on top of each other (e.g. M1 followed by R1). The fixation sequence in a given trial is presented in a stacked bar in which each coloured segment denotes a gaze fixation at a particular AOI, and the length of each segment corresponds to the duration of the fixation at the AOI.

Figure 3. 10 shows total fixation duration throughout all trials for all AOIs as coded by both rates.

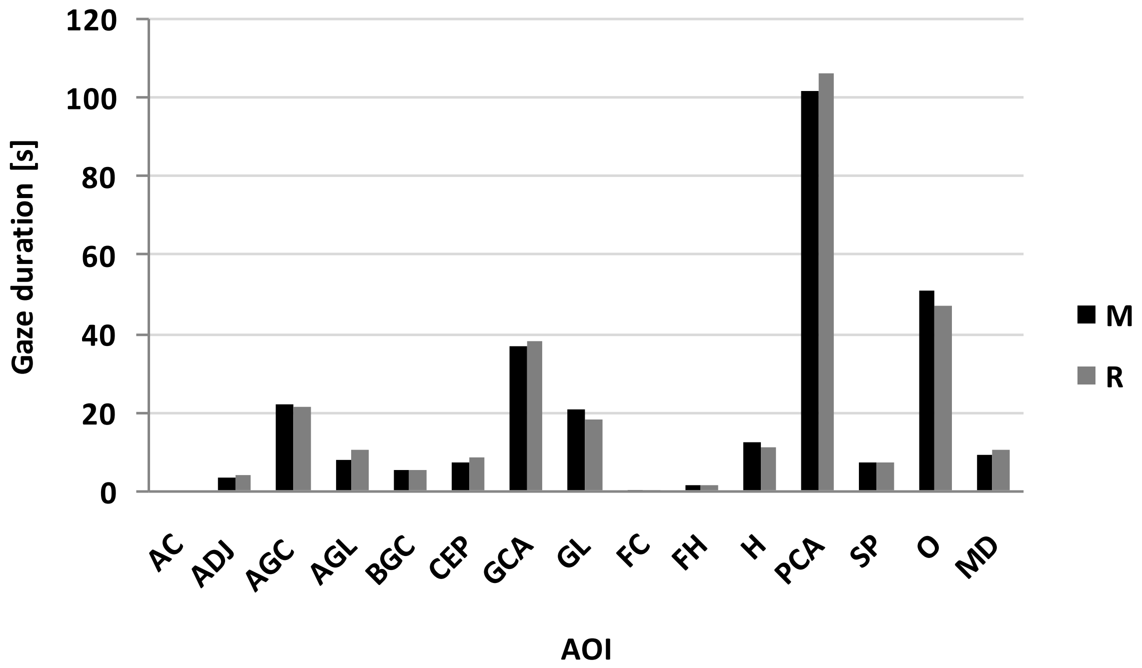


Figure 3. 10: Total gaze duration as coded by raters M and R.

Figure 3. 11 illustrates the differences between in representation of gaze behaviours when coding the objects only (A), and when coding using the proposed coding scheme (B).

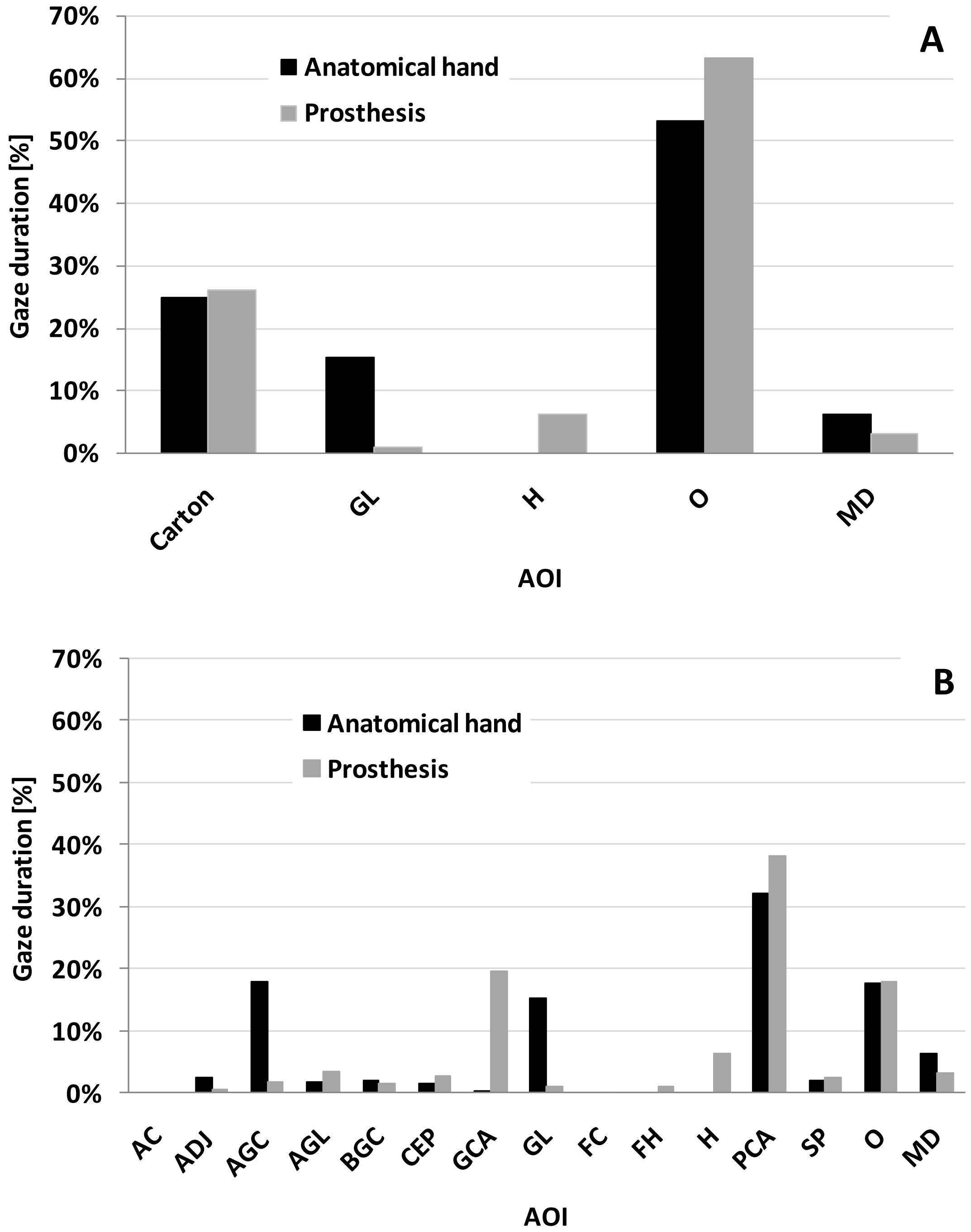


Figure 3. 11: Group mean normalised gaze duration at each AOI for both subjects and both conditions as coded by rater M; (A) when objects and hand only were considered, (B) when all AOIs of the coding scheme were considered.

### 3.5. Discussion

Gaze behaviour is task dependant (174) and hence appropriate task selection was important. In the introduction, a number of task requirements were introduced and based on these, pouring water from a carton in to a glass was proposed. The task is multi-stage, is clearly common in everyday life situations and was shown to be achievable with a prosthesis, even by subjects who had no previous experience. In addition, the task took seconds to be completed under either testing condition, which allowed gathering a large number of repeated trials in a relatively short testing session (1 ½ hour), a useful feature when working with eye tracking systems.

An experimental setup has been designed for this task that appears to provide reasonably consistent performance between trials and between subjects under each testing condition. Generally, the initial inspection of the arm movement from the gaze video data suggested that the carton was reached and grasped in a similar manner across each testing session and, to some extent, consistently between subjects under each condition. Pouring action, was also similar between subjects; the carton was located above the glass then gradually tilted. However, when comparing the arm movement under the two testing conditions from visual inspection of the gaze video data, prosthetic hand movement showed marked differences from the anatomical hand; particularly during water pouring. When the prosthetic hand was used, the carton was tilted predominantly using shoulder abduction. This was not observed when the anatomical hand was used and this and other observations will be discussed in detail in the following Chapter.

By examining the gaze sequence, a main gaze fixation difference between the two subjects appeared while using the anatomical hand. That is, in contrast to subject 1 who mainly fixated at PCA during the water pouring, subject 2 fixated the Glass and Above GCA. This difference is probably not functionally significant since in both cases the intention was probably to monitor the pouring action. Interestingly, both subjects showed similar gaze sequences when they used the prosthesis. Undoubtedly, because of small number of trials and subjects these findings remain at this stage as interesting observations that deserve further investigation.

The coding scheme introduced in this Chapter, despite the strictly defined AOIs and the way of accounting for the overlap between AOIs, gaze coding is still carried out by exploring the gaze video data frame by frame and visually judging which AOI is being fixated. Therefore, there remains a subjective element to the coding scheme. However, the inter-rater reliability investigation revealed results in favour of the clarity of the coding rules and reliability of the introduced coding scheme. From the gaze sequence data illustrated in Figure 3. 8 and Figure 3. 9 and gaze duration in Figure 3. 10, the agreement between the two raters, in a broad sense, is observable. Nevertheless, in a few cases, location of the gaze fixation was observed to still depend on the rater’s opinion and this seems to have an impact on the coding results. For instance, on many of the occasions when the raters disagreed, the gaze was fixating marginally between adjacent AOIs. Further, it is likely that the confusion matrix might not yet be fully optimized for this task. Another common occasion of disagreement is when the raters had to decide whether the gaze pursued the hand. Perhaps because coding was completed frame by frame thus pursuit movement was difficult to detect. Considering the velocity profile of the gaze cursor while coding would help in this respect.

Statistical tests in general demonstrate the reliability of both defining the task duration and coding the gaze data according to the coding scheme. However, using the ICC to establish the inter-rater reliability of such sequential data is less than ideal. More complex statistical analysis of sequential time series data should be considered in future work which takes in consideration the gaze sequence as well as the gaze duration (195). The ICC does not compare the gaze sequence but rather the sum of gaze duration at AOIs. Generally, the disagreement between raters was mainly on coding of short fixation durations that emerge between other long fixation durations which the raters broadly agreed on. Therefore, the sum of gaze duration at AOIs was minimally influenced by the disagreement between raters.

As Figure 3. 11 shows, the coding scheme was able to show distinct differences between the two hands likely due to the way AOIs were defined. The gaze behaviour differences were mainly in the fixation duration at Above GCA, GCA, Glass, Hand and PCA. In detail, prosthesis use, comparing to the anatomical hand use, seemed to require more visual attention to GCA, and Hand and less attention to Above GCA and GL. This result is in line with the author's pilot findings (193) in which it was showed that the distribution of gaze focus appeared to change when the prosthesis was introduced. Interestingly, two of the AOIs that showed distinct differences between the two hands lie within the carton, which underpins the assumption regarding the importance of dividing the objects into a number of separate AOIs. Additionally, this supports the potential utility of the chosen task for answering the questions posed in the following chapters.

### 3.6. Conclusion

In order to quantify the differences between the two testing conditions objectively, a coding scheme based on functionally-relevant AOIs has been developed. This study reports, to author's knowledge, the first attempt to produce a detailed and reliable coding scheme that incorporates sub-parts of objects as AOIs defined by function, and this is likely to be of interest to other researchers studying gaze during complex tasks. Although the defined AOIs are exclusively applicable to the selected task, the method used to define AOIs in this work can be generalized.

In the following Chapter, the coding scheme is used to characterise the gaze behavioural changes over learning to use a myoelectric prosthesis. Additionally, the kinematic changes of the arm movement associated with learning to use the prosthesis will be explored. The investigation will involve performing the manual task identified in this Chapter in anatomically individuals; first, while using their anatomically hand (baseline) then while using a prosthesis (intervention). The prosthetic performance will be investigated over a number of sequential sessions intervened by training periods.

## Chapter 4: Changes in upper limb kinematics and gaze behaviour during learning to use a myoelectric prosthesis

### 4.1. Introduction

As discussed in previous chapters, relatively little is known about skill acquisition in upper limb amputee users of myoelectric prostheses. This preliminary study, that aims to inform future work with amputee subjects, reports on visuomotor performance behaviours as anatomically intact subjects learn to use an upper limb myoelectric prosthesis. It was chosen to study performance on an ADL task, as it is clearly clinically relevant, yet has received little attention in the literature. Characteristic differences between performance with the anatomical hand and the prosthesis are identified, and more importantly, behaviours that change with learning and hence define parameters associated with skill acquisition are identified.

As this was the first reported study of visuomotor behaviour in learning to use a prosthesis, a wide range of measures that have previously been shown to either differentiate between prosthetic and anatomically intact reaching, or to reflect motor learning in anatomically intact subjects were investigated. Subjects' performance on a well-validated measure of hand function (Southampton Hand Assessment Procedure, or SHAP) (25) was also recorded, which provided a 'gold-standard' measure of functional ability of both arms (anatomical and prosthetic) with which to compare changes in other measures. The SHAP test was chosen rather than the ACMC, as the latter test is designed to assess myoelectric hand control exclusively and hence cannot be used to assess anatomical hand performance. In addition, the researcher (Mohammad Sobuh) did not have significant previous experience in clinical training and follow up of myoelectric prosthesis users (a role normally given to Occupational Therapists), and the reliability of the ACMC has been shown to be influenced by this type of experience (113). The outcome measures are discussed in the following two sections:

#### *4.1.1. Kinematics*

Unlike pointing tasks, functional task performance using a myoelectric prosthesis involves complex sequences of spatial movements, coordination between the trajectories of the prosthetic and anatomical joints and interaction between the prosthetic hand and objects. In contrast to studies of pointing tasks in which only small differences have been observed between prosthetic and anatomical arm performance (e.g. (7, 133, 145)), previous studies of functional performance have shown large differences in joint kinematics (139), arm movement and hand aperture characteristics and task completion time between anatomically intact subjects and body powered and myoelectric prosthesis users (5, 8). However, as described in Chapter 2, Section 2.10.4, very little is known about the effects of practice on upper limb kinematics in functional tasks that require active involvement of the prosthetic hand, such as activities of daily living (ADLs).

It is known that upper limb kinematics during the performance of functional tasks differ between amputees and anatomically intact controls, as amputees adopt compensatory patterns of movement, at least partly in response to the limited degrees of freedom of upper limb prostheses (134). However, it is not known whether it is possible to learn to adapt to the reduced degrees of freedom by refining the compensatory patterns over time. Therefore, it was chosen to record joint angle trajectories at the shoulder, elbow and wrist when a prosthesis is first introduced and to investigate whether any compensatory patterns change with practice.

When presented with a challenging upper limb task, variability arises as a result of exploring different control strategies in order to find the best solutions (196). With practice, a decrease in the performance variability can be observed over multiple attempts to perform a manual task (196). Typically, two aspects of variability have been widely investigated; variability in execution and variability in the outcome of the movement (196). For instance, as a function of practice, the variation in joint angles between trials reduces (197), and variation in movement trajectory (198) and movement peak velocity decrease over time (199). Similarly, with practice, endpoint variability decreases (199) and movement velocity increases without affecting the endpoint accuracy (198). In this study, it was decided to study the variability in execution, using metrics of variability of acceleration trajectories measured at the forearm. This approach may be used outside of the laboratory with simple and low cost instrumentation (accelerometers) and hence has potential to be applied clinically (200). The question was asked “Does variability in forearm acceleration trajectories decrease as subjects learn to use their prosthesis?”.

As discussed in Chapter 2, a small number of papers have reported on the characteristics of wrist velocity and/or myoelectric hand aperture control during reach to grasp in prosthesis users (8, 117) and with learning to use a prosthesis (138, 151-153). Over practice, control of the hand state improves (151, 153). This study aimed to report on the changes to both hand aperture control and arm velocity in subjects learning to use a conventional (i.e. non-proportional) prosthetic hand.

### 4.1.2. Vision

Despite the widespread belief that vision plays a critical role in prosthetic use (5-10, 104), and despite the extensive literature on the role of vision in performance of manual tasks (38, 49, 51-54, 179, 192, 201) and when learning to use tools (56, 68, 202, 203), at the start of the PhD, there were no studies of gaze behaviour in upper limb prosthesis users. Earlier studies interpreted certain kinematic characteristics as a possible indication of relying on visual feedback to use the prostheses such as the existence of plateau in the hand aperture profile during reach to grasp objects (resulting from delay in the initiation of hand closing around the object) (5, 8). Wing and Fraser, in an informal investigation, also observed that in 4 attempts out of 5, an expert trans-radial body powered prosthesis user was, and unlike when performing with contralateral anatomical hand, unable to grasp a wooden object under no visual access to the object (5). Also, the need to rely on vision was one of the main complaints expressed by prosthesis users in a survey by Atkins (9). Despite the improvement to upper limb prostheses since the time of this survey in 1996, to date, the reliance on visual feedback remains a major problem to users (204).

As discussed in Chapter 2, since acquiring and processing visual attention demands use of finite attentional resources, the oculomotor system attempts to optimise its use of visual information (54). It has been proposed that in anatomically intact individuals visual behaviours during performance of a well-learnt task are therefore indicative of minimal overt attention and non-relevant areas are rarely if ever fixated (205). Further, when using the anatomical hand to complete tasks, such as ADLs, which can be described a sequence of sub-actions[‡], gaze also behaves in characteristic ways. Typically, gaze is brought to objects/areas that hold important information for the sub-action in advance of the sub-action being started (54), and usually leaves the object seeking further information for subsequent sub-actions before the previous sub-action is completed. Given the similarity in the sequence of sub-actions of a task between subjects (54), gaze normally follows a scan path in which it sequentially fixates at specific areas on the relevant objects and specific to the particular task (192).

As also discussed in Chapter 2, when learning to use a hand tool, such as a gripper, or surgical laparoscope, gaze behaviour is disturbed. The timing and sequence of gaze fixation at AOIs may change (62, 68). Also, fixation at new AOIs may be observed such as fixating at a tool

[‡] Sub-actions are defined as "simple actions that transform the state or place of an entity through manual manipulation" (54).

tip (68). As a result a very different visual scan path may be seen (62), or the normal visual scan path may be broadly maintained but with interruption periods during which the gaze fixates at new AOIs (62). With learning, the number of transitions tends to decrease, as more time is spent fixating the target rather than the tool (62, 68).

Changes to gaze behaviour with learning have been reported in other domains (206). Although the changes that occur to gaze behaviours with learning vary to some extent between tasks, the overall changes can be interpreted as enhancement of visual processing (206, 207). Gaze behaviour has also been found to differentiate between experts and novices (68, 208, 209). Experts' gaze behaviour can be characterised by fewer gaze fixations which stereotypically focus on task-related AOIs and most often precede the intended actions. Novices' gaze behaviour in turn is more scattered and tends to closely guide the performance (when directing objects, tracking the object movement is common) (68).

In this study, the following questions were asked "In what way does gaze behaviour change from use of a subject's anatomical hand to using a prosthesis?"; and "How does gaze behaviour change with learning to use a prosthesis?". To answer these questions, it was planned to study gaze fixation on critical areas in the scene ahead, AOIs, as discussed in Chapter 3. The sequence of fixations on AOIs was investigated to show whether introducing a prosthesis changes the visual information required for successful task performance, and whether after training, the behaviours return to normal or whether a new behaviour is developed. Additionally, the number of transitions between AOIs was calculated to reflect the stability of the gaze pattern. The percentage of time spent fixating at each AOI was also calculated. Based on the functional interpretation of the fixation at each AOI (or set of AOIs), this analysis allows conclusions to be drawn about the visual attention required during anatomical and prosthetic hand use and the effects of practice on visual attention.

## 4.2. Methods

The study was approved by the University of Salford Research Ethics committee (Ref # REPN09/174). Seven anatomically intact individuals (four males and three females) with a mean age of 36 years (range: 26-48 years, standard deviation (SD): 10 years) agreed to participate in the study and gave informed consent. Six subjects were right handed and one subject was left handed. All subjects were able to complete upper limb functional tasks comfortably without glasses or contact lenses. All data were collected in the Movement Science Laboratory at the University of Salford, Salford, UK.

The study was a quasi-experimental AB design (baseline followed by an intervention). Subjects' normal upper limb kinematics and gaze behaviour during the performance of an ADL task were evaluated in a single visuomotor performance session (V1) which formed the baseline for task performance with the intact anatomical hand (Table 4. 1)[§]. Following this, they were fitted with a myoelectric prosthesis simulator and were then evaluated with the prosthesis three times; once immediately on receiving the simulator (V2), approximately a week and then 2 weeks after initial fitting (V3 and V4 respectively). Additionally, subjects were evaluated in five further separate clinical sessions in which they performed the Southampton Hand Assessment Procedure (SHAP) (25): once with the anatomical hand after V1 (SHAP1) and four times with the prosthesis stimulator (SHAP2-SHAP5) as shown in Table 4. 1.

As discussed before, SHAP comprises completion of 26 self-timed tasks (12 abstract object tasks and 14 ADLs) and is a validated clinical measure of hand function (25). The clinical evaluation sessions were performed on different days to the visuomotor performance sessions, to avoid fatigue. In addition to providing a measure of hand function, performing SHAP also provided an opportunity for subjects to practice a range of tasks using the prosthesis.

According to Prof. Peter Kyberd (one of the developers of the SHAP)[**], the functionality index is likely to plateau after completing about 10 sessions of SHAP in an average anatomically intact subject while learning to use a myoelectric prosthesis. During the pilot work (193), the subject required a considerable time (~ 45 minutes) to complete each SHAP session using the prosthesis and also she experienced muscle fatigue following completion of SHAP. Therefore, it was not possible to conduct more than one SHAP session per testing day and these were spread over the period of the study as shown in Table 4. 1. The design was a compromise between the "best guess" of an ideal target (10 SHAP sessions) and the constraints on the number of visits subjects would tolerate.

[§] The experiment reported in this chapter involved the subjects completing two visuomotor sessions (V0, and V1) and two SHAP sessions (SHAP0 and SHAP1) in the baseline (while using the anatomical hand). Initial analysis, however, showed no evident differences in the performance between either V0 and V1 or SHAP0 and SHAP1. Therefore, from all data gathered in the baseline, it was decided to analyse only data gathered in V1 and SHAP1.

[**] Personal communication with Prof. Peter Kyberd.

| | Condition | Session |
|---|---|---|
| 0 | Anatomical hand | V1: Kinematics & gaze behaviour |
| | | SHAP1 |
| | Prosthesis simulator | V2: Kinematics & gaze behaviour |
| | | SHAP2 |
| | | SHAP3 |
| | | V3: Kinematics & gaze behaviour |
| | | SHAP4 |
| | | SHAP5 |
| 2 weeks | | V4: Kinematics & gaze behaviour |

Table 4. 1: Experimental design.

### *4.2.1. Instrumentation*

#### *4.2.1.1. Myoelectric prosthesis simulator*

A s described in Chapter 3, a similar prosthetic socket which could be fitted over the anatomical arm was customised for every subject. The socket was equipped with a single degree of freedom electrical hand (RSLSteeper "Select" Myo Electric hand (size 8 ¼″)), whose opening and closing was controlled via EMG signals from 2 socket-located electrodes (further detail on the prosthesis simulator and its control can be found in Section 3.2.3.1, Chapter 3). As a reminder, at the time of the experiment, only a left prosthetic hand was available and therefore this prosthesis was customised for the left side for all subjects, and used throughout this study.

#### *4.2.1.2. Kinematic data*

Kinematics were calculated from 3D reflective marker position data that were collected at 100 Hz using a ten camera Vicon 612® motion capture system (Vicon Motion Systems, Los Angles, USA).

In order to minimise effects of skin movement on data capture, the CAST method (calibration anatomical systems technique) (210) was chosen. The CAST method uses clusters of markers (technical markers) on each segment from which local "technical" coordinate frames are defined. A second set of co-ordinate frames, the "anatomical" frames, is then defined by markers placed on the anatomical joints (anatomical markers). A static calibration trial was recorded to define the location of the anatomical with respect to the technical co-ordinate frames. During movement trials (i.e. task performance), only technical markers were then recorded and post data collection the anatomical markers may then be reconstructed from their known locations in the technical frames.

The positions of technical and anatomical markers on the body's segments are illustrated in Figure 4. 1. Plastic (polyethylene) plates of 6mm thickness were moulded to the shape of the upper limbs' segments and sternum and used to securely mount the technical markers. Accordingly, three technical marker clusters were used; each technical marker cluster consisted of four markers. Although only 3 markers are required to completely specify a cluster's associated technical frame location and orientation (pose), a fourth is added to allow reconstruction in the event of one marker being obscured from camera view. The extent of prosthetic hand opening (scalar distance between the fingers) was defined by one marker on the thumb and another on the index finger. Additionally, 4 more markers were attached to the carton as illustrated in Figure 4. 2. Detailed description of marker positions is listed in Table 4. 2.

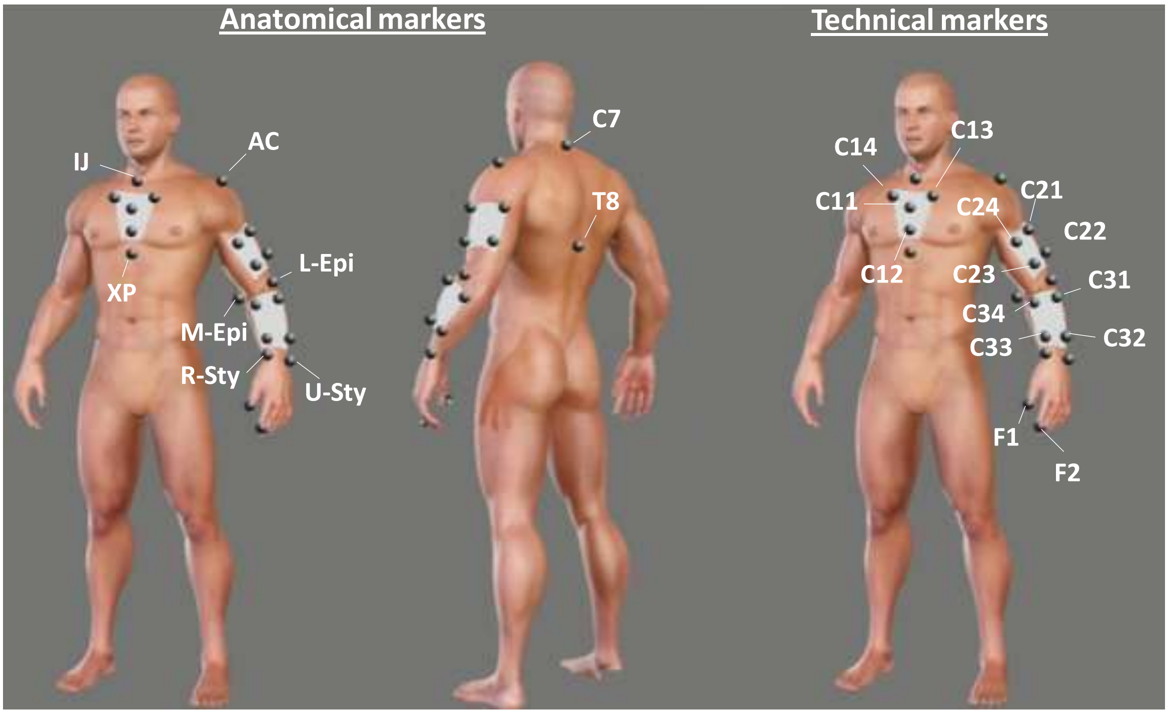


Figure 4. 1: Anatomical and technical marker setup for the body's segments (adapted from (211)).

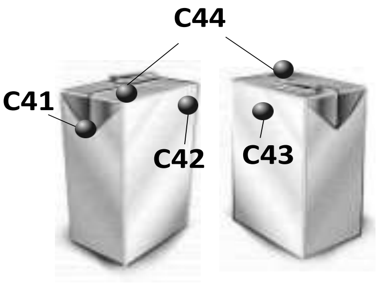


Figure 4. 2: Marker setup on the carton from different viewing angles.

| ***Anatomical markers*** | ***Marker label*** |
|---|---|
| Most caudal-lateral point on the ulnar styloid | U-Sty |
| Most caudal-lateral point on the radial styloid | R-Sty |
| Most caudal point on medial humeral epicondyle | M-Epi |
| Most caudal point on lateral humeral epicondyle | L-Epi |
| Most dorsal point on the acromioclavicular joint | AC |
| Spinal process of the 7$^{th}$ cervical vertebra | C7 |
| Spinal process of the 8$^{th}$ thoracic vertebra | T8 |
| Deepest point of Incisura Jugularis | IJ |
| Xiphoid process: Most caudal point on the sternum | XP |
| ***Technical markers*** | |
| Torso cluster: Middle of the sternum | C11-C14 |
| Upper arm cluster: Middle of the lateral boarder of the upper arm | C21-C24 |
| Forearm cluster: Middle of the lateral boarder of the forearm/ socket | C31-C34 |
| Carton: Uppermost quarter of the carton | C41-C44 |
| Middle of tip of the thumb | F1 |
| Middle of tip of the index | F2 |

Table 4. 2: Reflective marker placement. Note: When the prosthesis simulator was used, U-Sty and R-Sty markers were placed on the wrist unit and M-Epi and L-Epi markers on the socket over the medial and lateral humeral epicondyles, respectively.

Once all of the markers had been placed on the subject, he/she was asked to sit on a chair with both hands resting on the table top. While maintaining this position, the marker data were captured for a few seconds (static trial). These data were used later on to construct the body segments. After that, and after removal of the anatomical markers, the subject performed the following movement sequence (“functional trial”):

1. $90^0$ shoulder flexion;
2. Shoulder extension to neutral position;
3. $30^0$ shoulder extension;
4. Shoulder flexion to neutral position;
5. $90^0$ shoulder abduction;
6. Shoulder adduction to neutral position;
7. Shoulder circumduction (two turns).

   These data were used to identify the functional joint centre of the shoulder (Appendix G) and the models used for this calculation and for describing elbow and shoulder joint angles are described in section

##### *4.2.1.3. Gaze data*

Gaze data were captured using iView X™ HED 2 (SenseMotoric Instruments GmbH, Tellow, Germany) combined pupil and corneal reflection eye-tracking system. The system is described in Section 3.2.6, in Chapter 3. Briefly, the system comprises two video cameras, one of which captures an illuminated image of one of the eyes on a mirror at a sampling rate of 50 Hz (eye camera), and the second captures the scene ahead at a sampling rate of 25 Hz (scene camera). The camera system is connected via a USB cable into an iView workstation (a laptop running iView X™ software) in which video data is processed in real time to display at the end the scene video with a superimposed crosshair gaze cursor that corresponds to the instantaneous gaze position in the scene ahead (point of regard).

### ***4.2.2. Task performance***

The ADL task performed in all visuomotor performance sessions (V1-V4) involved reaching with the left hand for a (9.5 x 7 x 23 cm) squeezable juice carton (filled with 200 ml of water), picking it up, then pouring all of the water from the carton to a glass. Finally, the subject was required to place the carton back at its starting point, release the carton and return the hand to its starting point (Figure 4. 3).

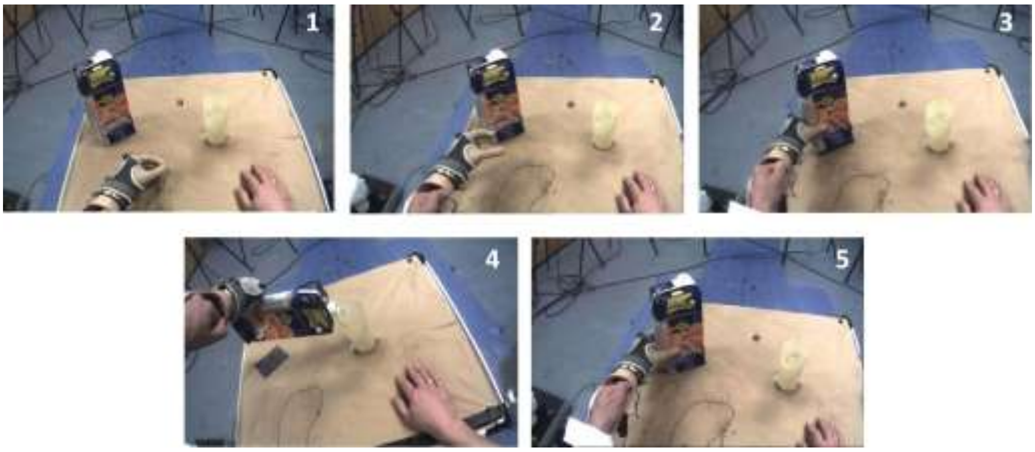


Figure 4. 3: Task performance (1: Reaching start point, 2: Reaching in progress, 3: Reaching endpoint/Manipulation phase start point, 4: Manipulation in progress, 5: Manipulation endpoint).

At the start of each visuomotor performance session (V) the subject was seated on a chair with his/her back resting against the chair's back and with their midline of the torso approximately aligned with the midline of the table. The upper arms were at the side of the body, elbows in a $90^0$ flexed position, and both hands resting comfortably on the table top as seen in Figure 4. 4[††]. The location of the hands when resting on the table were marked on paper before the start of V1 to ensure a similar arm posture and hand location at the start and end of each trial, throughout the series of experiments. The carton was placed within a comfortable reach from the left hand's start point, such that the subject was not required to lean to perform the task (approximately 30 cm from the proximal edge of the table, oriented with its posterior wall rotated $60^0$ clockwise relative to the proximal border of the table). This location allowed for easy access to the carton during grasping and reduced the occurrence of occlusion of finger markers (see Figure 3. 6 in Chapter 3).

Prior to starting each attempt at the task, the subject was instructed to focus on a marked "gaze reference point" (GRP) in the centre of the table (approximately 10 cm from the distal edge of the table) to prevent subjects from fixating the carton prior to task onset. Only then was the subject instructed to begin the task. During task performance, subjects were allowed to move their eyes freely. Furthermore, head movements during task performance were

[††] Note that the natural resting position of the anatomical hand differed from the resting position of the prosthetic hand; the anatomical hand was kept flat with the palm facing downwards, while prosthetic hand was pre-oriented in the mid-position. Although, it would have been possible to ask subjects to mimic the prosthetic resting position when the anatomical hand was tested, this would not have reflected the normal way of performing the task.

unconstrained. At the end of each trial, subjects were instructed to return their gaze to the GRP. When the prosthesis was used, the table was moved forward relative to the chair to accommodate the extra-length of the prosthesis. Subjects were instructed to repeat the ADL task 12 times in each session and the first 10 trials which showed good visibility of reflective markers and gaze cursor were used for analysis.

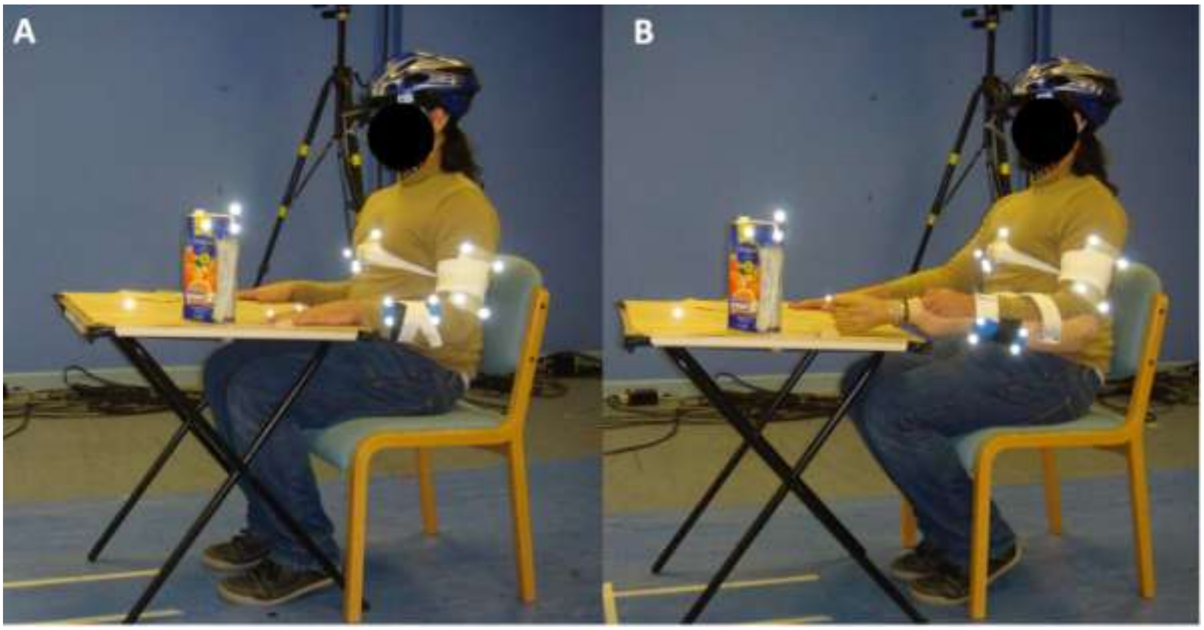


Figure 4. 4: Experimental and marker setup: When the anatomical hand was used to complete the task(A), when the prosthesis was used (B). Note: The table was moved to accommodate the extra length retained by the prosthesis. Also note that the different resting orientation of the anatomical and prosthetic hand.

## 4.3. Data analysis

### *4.3.1. SHAP sessions*

The SHAP score (or the index of functionality IOF) is calculated based on the time taken to complete each of the 26 SHAP tasks that cover the six prehensile patterns (see Figure 2. 3 in Chapter 2), normalised to 100. The number of tasks assigned for each pattern varies and is proportional to the estimated frequency of use of the prehensile patterns in everyday life (25). To calculate IOF, a functionality profile for each one of the six prehensile patterns is calculated. The functionality profile (or z score) of prehensile pattern $i$ ($i$=1..6) is calculated as the time for prehensile pattern $i$ minus the mean time for pattern $i$ in the normative sample, all divided by the standard deviation of the times for pattern $i$ in the normative sample. This process is repeated for all six patterns and finally, the IOF is calculated as square root of the sum of the squared z scores, normalised to 100. This is a measure of the Euclidian distance in

6 dimensional space of the person's score relative to the normative sample. The resulting IOF at the end is expressed out of 100; where above 95 is the expected normal functionality (118). Functionality profiles and the overall IOF were obtained using the web-based software produced by the developers of the evaluation tool (http://www.shap.ecs.soton.ac.uk/entry.php) (25).

### *4.3.2. Visuomotor sessions (V sessions)*

Kinematics and gaze data were recorded on separate systems with no automated synchronisation between the systems. Relevant points in the data sets that could be identified from both the gaze video and from kinematics were used to segment the trials, as described in more detail below.

#### *4.3.2.1. Kinematic data*

Marker data were labelled in Vicon workstation software *v.* 5.1 (Vicon Motion Systems, Los Angles, USA) and then exported to Visual 3D software v4.75.36 (C-Motion, Inc., Germantown, MD, USA) for subsequent processing. Data were first filtered, forward and backwards to avoid phase shift, using a 4$^{th}$ order Butterworth filter with a cut-off frequency of 6 Hz.

The following section describes first the calculation of accelerations with gravity (simulating accelerometer signals), hand aperture, wrist velocity and other variables derived from these data. The next section describes how the acceleration and hand aperture data were used to segment the trials into reaching and manipulation. This is followed by a description of the calculation of variability in acceleration trajectories in both reach and grasp and finally by a final section on the calculation of joint angles. The steps taken for data processing are illustrated in Figure 4. 5

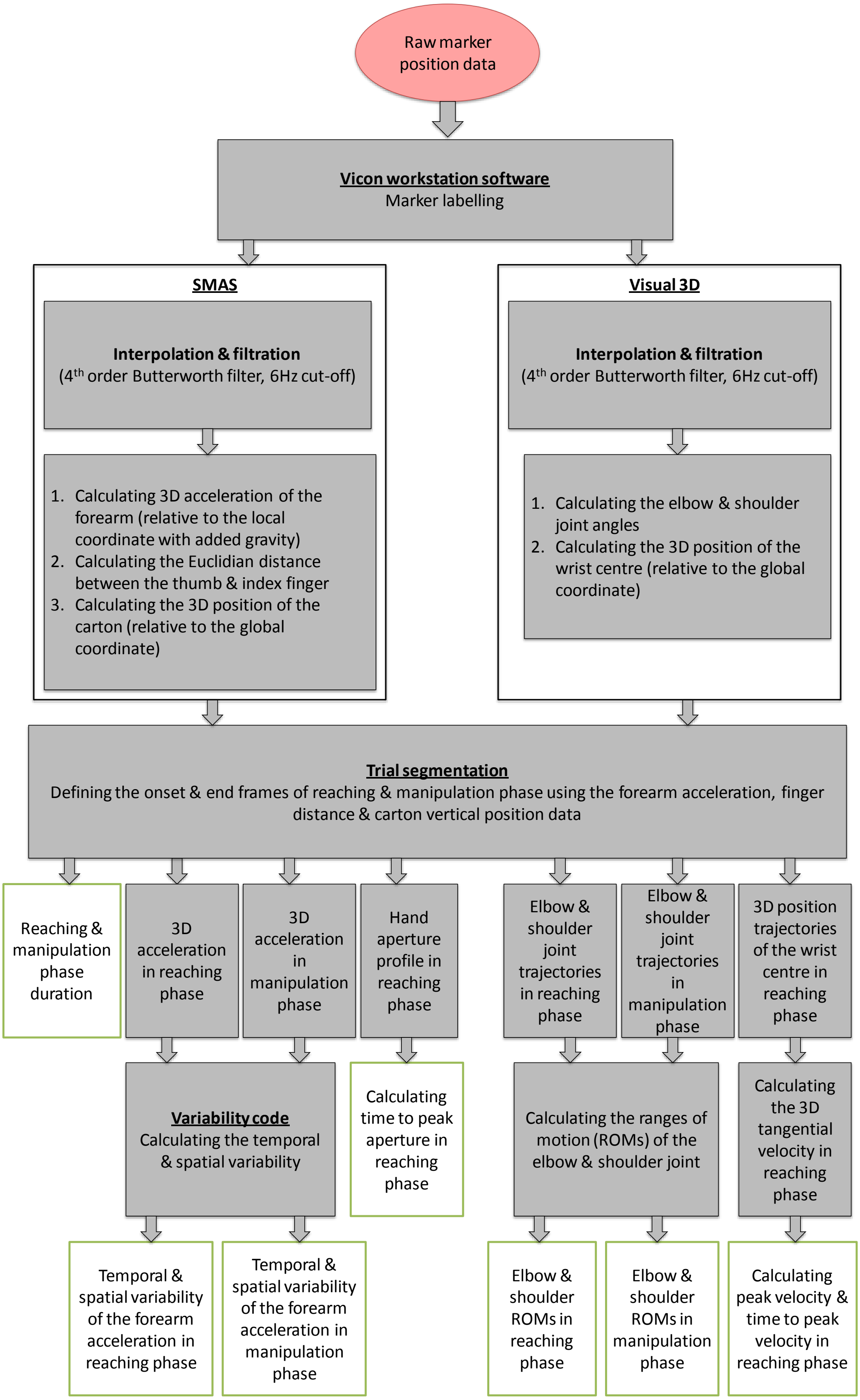


Figure 4. 5: A flow diagram showing the steps taken to process marker data and to derive different kinematic variables (the white boxes are final outputs).

*Joint angle calculations*

Visual 3D was used to calculate the joint angles. For this purpose, first, the local coordinate frames (joint coordinate frames (JCF)) were defined for the trunk, upper arm and forearm using the anatomical markers in a static trial. In Visual 3D, to define the JCF for the trunk, the origin was considered to be the mid-point of the line connecting the centres of the IJ and C7. The Y axis was parallel with the line connecting mid-point between XP and T8 and the origin, pointing upward. Z axis was the line perpendicular to the plane formed by XP, T8, and the origin of the trunk JCF, pointing to the right. X axis was the line perpendicular to the Z and Y axis, pointing forwards.

For the (left) upper arm, the origin was considered to coincide with the shoulder's centre of rotation (SCR) (SCR definition is described in Appendix G). The Y axis was parallel to the line connecting the mid-point between M-Epi and L-Epi and SCR, pointing upward. The X axis was the line perpendicular to the plane formed by SCR, M-Epi and L-Epi, pointing forward. The Z axis was the line perpendicular to the X and Y axis, pointing to the right.

For the (left) forearm, the origin was considered to be the mid-point of the line connecting between the centres of the M-Epi and L-Epi markers (elbow's centre of rotation (ECR)). The Y axis was parallel to the line connecting the ECR with the mid-point between the centres of M-Epi and L-Epi markers, pointing upward. The X axis was the line perpendicular to the plane formed by ECR, U-Sty and R-Sty, pointing forward. The Z axis was the line perpendicular to the X and Y axis, pointing to the right.

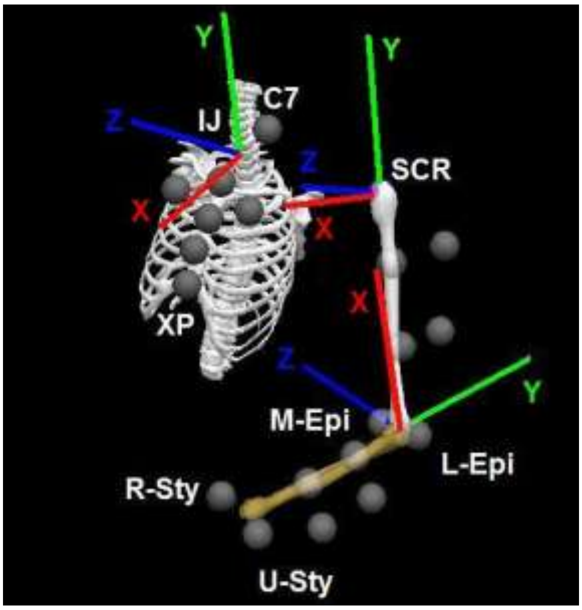


Figure 4. 6: Joint coordinate system (JCF) for the trunk, shoulder and forearm segments.

In dynamic trials, at each frame, the JCF of the three segments were re-constructed from the pose of each technical coordinate frame. The Cardan angles with a sequence X-Y-Z (212), were used in Visual 3D to describe the angular relationships between adjacent JCFs (trunk and upper arm JCFs, and upper arm and forearm JCFs). The three rotations were described as follows:

1. Rotation of a segment relative to its proximal segment about the X axis described as joint adduction-abduction motion, and;

2. Rotation about the Y axis described as joint internal-external rotation motion. and;

3. Rotation about the Z axis described as flexion-extension motion.

Elbow flexion-extension, shoulder flexion-extension, shoulder abduction-adduction and shoulder rotation were considered in the context of this thesis due to their clinical relevance. The average ranges of motion (ROMs) of the shoulder flexion-extension, adduction-abduction, and rotation, and elbow flexion-extension were calculated. To calculate the average ROM, the maximum value in the joint trajectory was subtracted from the minimum for each trial and then the average ROM was calculated across all trials of a given evaluation session.

*Forearm accelerations*

Data of the prosthetic and anatomical forearm marker clusters (C31, C32, C33, C34 in Figure 4. 1) were exported from Vicon Workstation software to a custom-written MatLab software package (Salford Motion Analysis System **(**SMAS)) which was developed previously by the author's group at the University of Salford, Salford, UK (213). SMAS was used to interpolate and filter the data, using a $4^{th}$ order Butterworth filter with a cut-off frequency of 6 Hz. SMAS was used to also to derive the 3D linear acceleration of the origin of the forearm marker cluster in global coordinates. To calculate the linear acceleration from marker position data, a local coordinate frame was defined with its origin at C31as:

$X = (C32 - C31)/\| (C32 - C31)\|$

$I= (C32 - C31) \times (C33 – C31)$

$Z = I/\|I\|$

$Y = Z \times X$

The axes of this forearm local coordinate frame are illustrated in Figure 4. 7.

For each frame, rotation matrices were calculated between the global coordinate frame and the local coordinate frame. Then the position of the origin of the local coordinate frame was calculated in the global coordinate frame.

By double differentiation of the position of the origin, the instantaneous acceleration at each instant in time was derived, expressed in the global co-ordinate frame. To account for the gravity acceleration, a value of $9.81 m/s^2$ was added to the vertical component of the acceleration. Finally, to simulate the accelerometer outputs, the calculated acceleration (with added gravity) was transformed to the local coordinate frame.

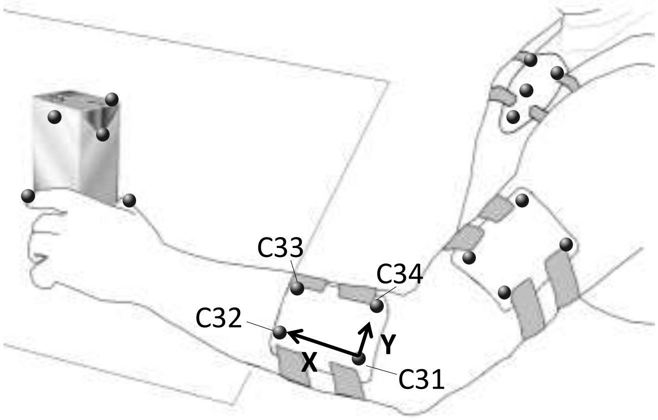


Figure 4. 7: The local coordinate frame of the forearm cluster that is used to calculate the forearm accelerations. Note: Z axis (not shown) is the perpendicular line to the plane formed by the X and Y axes pointing down (adapted from (214)).

The validity of the simulated accelerometer signals was investigated in a small study described in Appendix B.

*The velocity*

The velocity of the wrist joint centre was also computed by calculating the 3D position of the wrist centre for the trial duration in the global coordinate frame using Visual 3D software. Velocity at the wrist joint centre was calculated as follows:

1. A virtual marker was defined at the wrist joint centre, defined as the mid-point between markers U-Sty and R-Sty;
2. The 3D position of this virtual marker in the global coordinate frame was calculated for each instant in time;
3. The velocity component at time $i$ along each axis was calculated using the finite difference approach, as follows:

$$Vx(i) = \frac{x_{i+1} - x_{i-1}}{2\Delta t}$$

$$Vy(i) = \frac{y_{i+1} - y_{i-1}}{2\Delta t}$$

$$Vz(i) = \frac{z_{i+1} - z_{i-1}}{2\Delta t}$$

4. The resultant velocity was calculated as the square root of the sum of the squares of the velocity components.

From the velocity profile calculated in the reaching phase, peak velocity and time to peak velocity were measured.

*Hand aperture trajectories*

Hand aperture was calculated as the distance between the thumb and index markers in SMAS. From the hand aperture profiles, time to peak aperture was calculated. As finger markers were occluded in some trials, it was only possible to calculate hand aperture in 5 trials for each evaluation session.

*Task segmentation*

The task was subdivided into two phases: reaching and manipulation. The start of the task was defined as being when the x component of the forearm acceleration exceeded 0.18 m/s$^2$ above its resting mean value (for axes definition see Figure 4. 7). This threshold value was chosen after visual inspection of acceleration trajectories calculated for both anatomical hand use in V1 and prosthetic hand use in V2. More specifically, to identify this threshold value, the x component of the forearm acceleration of 6 trials (3 trials collected at V1 and another 3 trials collected at V2) for each subject were considered. First, these trials were over-smoothed in MatLab. Then the resting mean value for each trial was calculated from the first 500 frames during which the subjects maintained the resting position. A number of heuristically determined values above the resting mean were examined. The value 0.18 m/s$^2$ above the resting mean was identified to be the minimum value that would exclude all frames in which the hand was resting, while detecting the onset of movement at the earliest point in time.

The end of the reaching phase was defined by the onset of lifting of the carton. Specifically, the point when the vertical position of the centre of a cluster of 3 markers on the top of the carton in global coordinates exceeded a value of 10 mm from its resting location. A 10 mm threshold was chosen based on visual inspection of the kinematic data from the carton markers. Carton vertical position was preferred over other kinematic markers (e.g. hand aperture) because this point in the task was easier to define in the gaze video data than alternatives (such as when the fingers stop closing). The end of the manipulation phase was defined as the point at which the hand aperture opening velocity (rate of change of distance between the index finger and thumb markers) exceeded 0.05 m/s and the vertical position (in the global reference frame) of the carton marker cluster centre dropped below 10 mm above its original resting value.

The onset and termination of reaching and manipulation phases for each trial were then used to calculate task duration and phase completion time and to extract reaching and manipulation data from the 3D accelerations output and joint angle profiles. Task duration is defined as the summation of reaching and manipulation completion times.

*Temporal and magnitude variability of forearm-measured accelerometer signals*

Temporal and magnitude variability of linear acceleration trajectories were obtained using a previously designed algorithm coded in MatLab v7.0 (MathWorks, Massachusetts, U.S.A.) (200, 215). In this algorithm, the temporal variability between an arbitrary pair of trials is defined as the minimum time warping that is necessary to best align two trials in time while maintaining the temporal relationships between data points. To achieve this, the algorithm firstly calculates the Euclidean distance between each pair of acceleration data points[‡‡] ($p(i) = x(i), y(i), z(i)$ and $p'(i') = x(i'), y(i'), z(i')$) of the two trials, producing an error surface such as the one shown in Figure 4. 8. Here dark areas indicate a small distance between points and light areas indicate a large distance between points. A dynamic programming routine is used to calculate the path of minimum error across the diagonal of the error surface (white solid line in Figure 4. 8). Root mean square distance between the warping path and the ideal alignment path (a line representing a simple offset in time between each trial with no warping) is then calculated to represent the warping cost needed to align the two trials in time. The variability in magnitude is then measured by calculating root mean square error (RMSE) between the reference and the warped trial. This process is repeated for each pairing of the 10 trials and average values across all three axes for both the temporal and magnitude variability are calculated.

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[‡‡] $x(i), y(i), z(i)$ is a vector of accelerations in 3D space at time *i*.

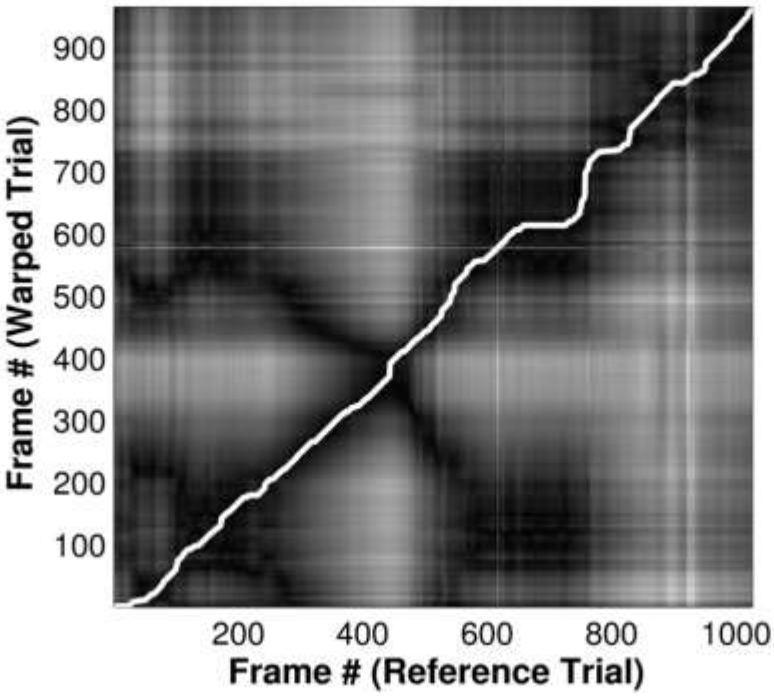



Figure 4. 8: An error surface representing the Euclidian distance between each pair of 3D acceleration vectors for two arbitrary trials A and B. The white line represents the path of minimum error (from (200)).

#### *4.3.2.2. Gaze data*

Gaze data were analysed as discussed in Chapter 3 (section 3.2.6) using BeGaze software v.2.3 (SenseMotoric Instruments GmbH, Tellow, Germany). In BeGaze, gaze events (fixation, saccades and blinks) are identified using a built-in dispersion-based algorithm.

The recorded trials were first segmented into reaching and manipulation components via visual inspection of the scene videos, based on the same definitions described in the previous section. Onset of reaching was defined to be the frame when the hand was first observed to start moving towards the target. Reaching ended when the carton first lifted off from the table and manipulation ended when the carton was in contact with the table and the fingers first lost contact with the carton following its placement back onto the reference point.

To assess agreement between segmentation based on kinematic data and the segmentation based on video data, an analysis was carried out. This is reported in Appendix C.

The gaze data were analysed using a coding scheme developed for the purpose of the study and described in Chapter 3 (see also (216)). As described above, 15 categories were defined (Table 4. 3); 14 of which correspond to an “area of interest” (AOIs) in the scene ahead

(Figure 4. 9), with the 15th corresponding to saccades, blinks and missing data. The inter-rater reliability of the coding scheme was examined and found to be high (ICC > 0.9, $p < 0.05$) (216). The researcher coded each frame for each trial against one of the AOIs using the BeGaze software.

| AOIs | Abbreviation |
| --- | --- |
| 1. Above Carton | AC |
| 2. Grasping Critical Area | GCA |
| 3. Above GCA | AGC |
| 4. Below GCA | BGC |
| 5. Adjacent to GCA | ADJ |
| 6. Glass | GL |
| 7. Above Glass | AGL |
| 8. Following Carton | FC |
| 9. Hand | H |
| 10. Following Hand | FH |
| 11. Spout | SP |
| 12. Pouring Critical Area | PCA |
| 13. Carton End-Point | CEP |
| 14. Other areas | O |
| 15. Saccades, blinks and missing data | MD |

Table 4. 3: Areas of interest (AOIs) for gaze coding.

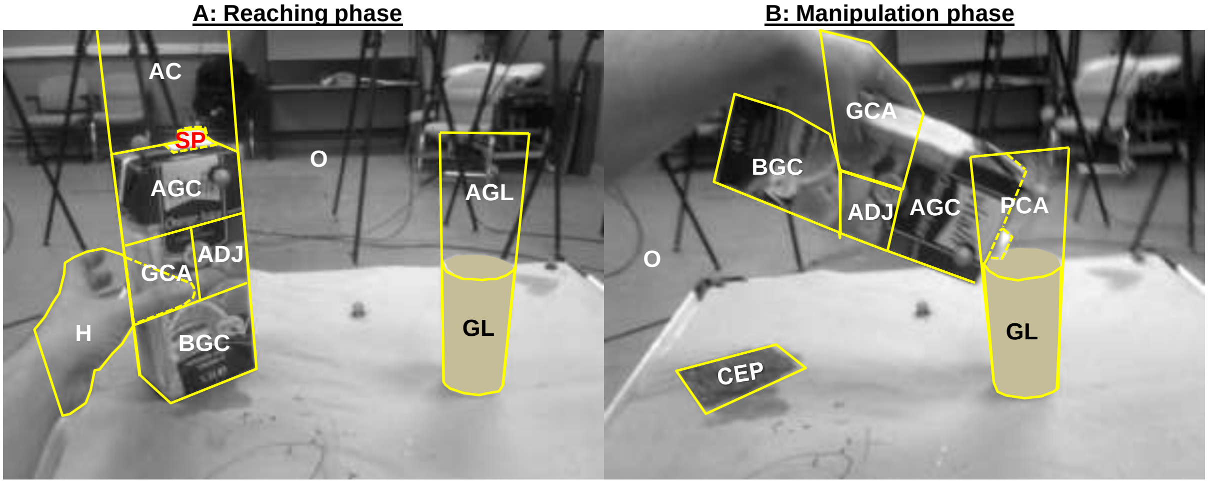



Figure 4. 9: The areas of interest (AOIs). Note: FH and FC AOIs[§§] are not shown.

For further gaze data analysis, first, for each phase of every trial, the gaze duration at each AOI was calculated. Gaze duration is defined as the sum of all fixations made on an AOI (194) in a given phase of a trial. The gaze duration for each AOI in a trial was normalised by the duration of the phase for each subject and for each visuomotor performance session (V). The normalised gaze durations were averaged over the 10 trials, then the group mean of gaze duration for all 7 subjects was calculated for each session. Then normalised gaze sequence was presented in stacked bars in which each area corresponds to the percentage fixation at a single AOI. For each trial, the number of transitions between AOIs was also calculated, after accounting for missing data.

### 4.4. Statistical analyses

Due to the larger number of AOIs and dependent relationships between them, the significant changes on gaze duration at AOIs over the course of the study were not statistically examined.

All Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows version 16.0, IBM SPSS Inc, Chicago, USA).

The normality of the data distribution in the explored variables was firstly checked using the Kolmogorov-Smirnov test. When the assumption of the normality was violated (reported p-value less than 0.05) in any variable, the set of variables to be compared were transformed to the log scale. In general, positive skewness was the main reason for deviation from normality in the data sets, thus log transformation was used to correct this skewness. In some cases,

[§§] FH takes place when the gaze pursues the hand (mainly while reaching), FC is when the gaze pursues the carton (mainly while transporting the carton).

when the value of a particular variable was zero, a constant (1) was added to all values of all variables to be compared together before transformation. In one variable (in reaching), reciprocal transformation was alternatively used when log transformation did not correct the normality. After transformation assumption of normality was examined once again and all transformed variables met the assumption of normality.

#### *4.4.1. The SHAP sessions*

The same data analysis was completed for the SHAP sessions in which SHAP1, SHAP2 and SHAP5 were firstly compared using one-way repeated measure ANOVA, and then planned comparisons between SHAP1 and SHAP2, and SHAP2 and SHAP5 were conducted. Statistical analysis for the SHAP sessions is listed in Appendix E.

#### *4.4.2. The visuomotor performance sessions (V)*

In this study, it was hypothesised that the effect of introducing a prosthesis would be evident from the changes to the SHAP, kinematic and gaze measures in each phase between V1 and V2. Learning (with practice), in turn, would be shown from changes to the explored measures in each phase when comparing V2 with V4. This comparison between sessions was planned before collecting the data. Also, it does not take in considerations all possible pairs. This comparison is known as a planned comparison (or planned contrast) (see (217) for further detail). The planned comparison accounts for the familywise error rate by breaking down the variance observed in the whole data set into independent components (contrasts); each component compares two variables independently from the other variables, thus $\alpha$ does not need to be corrected.

Therefore, for each of the explored measures, the main effect of sessions in each phase was investigated using one-way repeated measure ANOVA (except for the ROM and Gaze duration at AOIs). When the main effect of sessions was found to be significant (p-value $<.05$), a further comparison between sessions of interest was completed (V1 vs. V2 and V2 vs. V4). For this purpose, repeated contrast was conducted in which V1 is compared with V2, and then V2 is compared with V4. ANOVA results and planned comparison results are also listed in Appendix E.

Since changes in one ROM might affect other ROMs, all ROMs in each phase, for the three sessions of interest (V1, V2 and V4) were compared using a two-way repeated measures ANOVA. If the effect of sessions was significant and/or the interaction (sessions x joint

ROM) was significant, one-way repeated measures ANOVA was conducted for each joint ROM to explain the significant results. Following this, planned comparisons were conducted to determine between which sessions the difference was significant. Statistical analysis for ROM is also listed in Appendix E.

## 4.5. Results

Kinematic and gaze data of the left handed subject was compared to the 6 right handed subjects. As no evident difference was observed (see Appendix F), the means of variables for all subjects including the left handed one were used to derive the results discussed below. In all figures below, error bars indicate ± 1 standard deviation (SD) unless otherwise stated. Where appropriate, a square bracket with a single asterisk is used to indicate that the difference between two sessions was significant ($p < .05$).

### *4.5.1. SHAP scores and task completion time*

Table 4. 4 and Table 4. 5 show the mean SHAP indices of all subjects over the study period and mean time to complete the manual task for visuomotor performance sessions (V), respectively. Increasing SHAP index and decreasing task duration indicate improvement. SHAP index declined dramatically from 94 in the baseline session to 36.8 upon introduction of the prosthesis simulator. However, repeated performance of SHAP with the prosthesis simulator resulted in mean SHAP index increasing to 67.4. Time to complete the manual task increased from 9.3 s at baseline (V1) to 16 s at V2. However, with practice, it decreased to 12.6 s by V4. Repeated measures ANOVA showed a significant main effect of SHAP sessions, ($F$ (2, 12) = 283.35, p<.05). Planned comparison showed a significant decrease in SHAP index when the prosthesis was introduced ($F$ (1, 6) = 422.02, p<.05) and significant increase with practice ($F$ (1, 6) = 258.47, p<.05). As may also be seen in Table 4. 4, the time to complete each phase also increased at V2, and then declined with practice. Statistical analysis showed also a significant main effect of V sessions on task duration ($F$ (2, 12) = 34.57, p<.05). The task duration was significantly longer in V2 compared with V1 ($F$ (1, 6) = 43.21, p<.05) and significantly shorter after training in V4 compared to V2 ($F$ (1, 6) =11.45, p<.05).

Figure 4. 10 shows the mean reaching (A) and manipulation phase duration (B) as a function of trial for all sessions. From this figure, it is clear that both reaching and manipulation were completed consistently quicker in V1 and there was no obvious decrement in phase duration

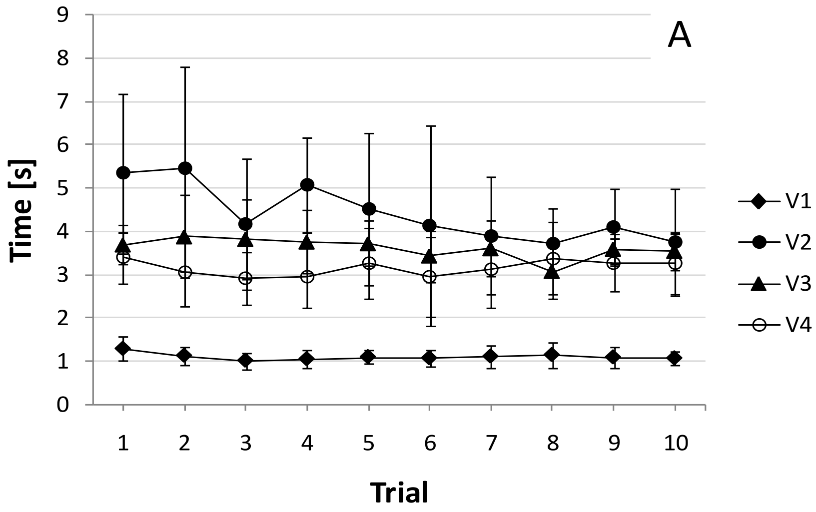
within-session. In contrast, V2 had both the longest task duration and highest within-session decrement in the phase duration.

| | SHAP1 | SHAP2 | SHAP3 | SHAP4 | SHAP5 |
|---|---|---|---|---|---|
| SHAP functionality index | 94 (1) | 36.8 (6.7) | 51 (3.3) | 60 (6.4) | 67.4 (4.5) |

Table 4. 4: Group means (± 1 group SD) of the SHAP functionality indices throughout the study period.

| | V1 | V2 | V3 | V4 |
|---|---|---|---|---|
| Task duration [s] | 9.3 (1.1) | 16 (2.7) | 13.7 (1.1) | 12.6 (0.8) |
| Reaching duration [s] | 1.1 (0.2) | 4.4 (1.1) | 3.6 (0.4) | 3.1 (0.6) |
| Manipulation duration [s] | 8.2 (0.9) | 11.6 (2) | 10.1 (1.3) | 9.5 (1.1) |

Table 4. 5: Group means (± 1 group SD) of time to complete the manual task, reaching, and manipulation phase duration across visuomotor performance sessions (V1-V4) throughout the study period.



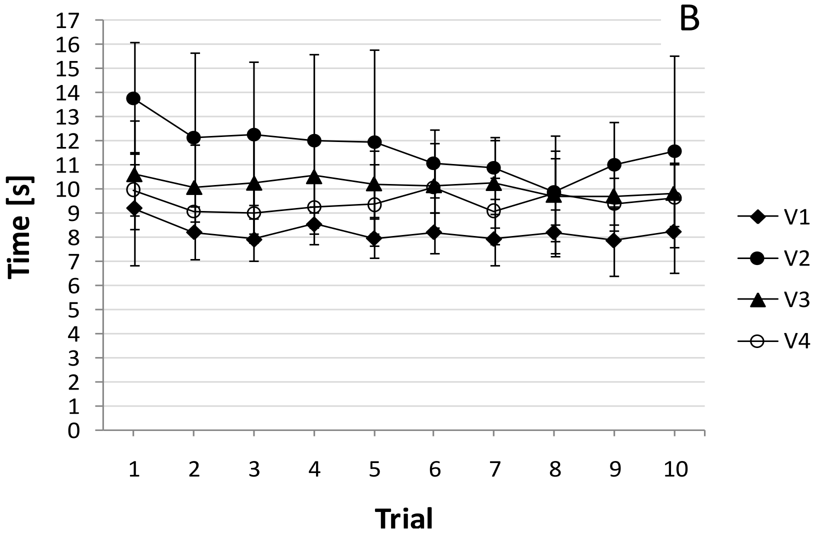




Figure 4. 10: Within-session, group means of the reaching phase duration (A) and the manipulation phase duration (B).

### *4.5.2. Kinematic data*

#### *4.5.2.1. Joint angles and ROMs*

Examples of the joint angle trajectories for all joints in reaching and manipulation phase in a representative subject are illustrated in Figure 4. 11 and Figure 4. 12 respectively. Figure 4. 13 shows the average range of motion of shoulder flexion-extension, abduction-adduction, and rotation, and elbow flexion-extension for all subjects for all visuomotor performance sessions in both phases. Prosthesis use predominantly significantly affected shoulder adduction-abduction during the manipulation phase ($F$ (2, 12) = 80.28, p< .05); the corresponding ROM dramatically increased from about 22° in V1 to about 70° in V2 (Figure 4. 13) and this was found to be significant ($F$ (1, 5) = 123.03, p<.05). With practice (i.e. by V4), ROM then declined slightly to about 64°, however, this was not found to be significant ($F$ (1, 5) = 0.55, p>.05).

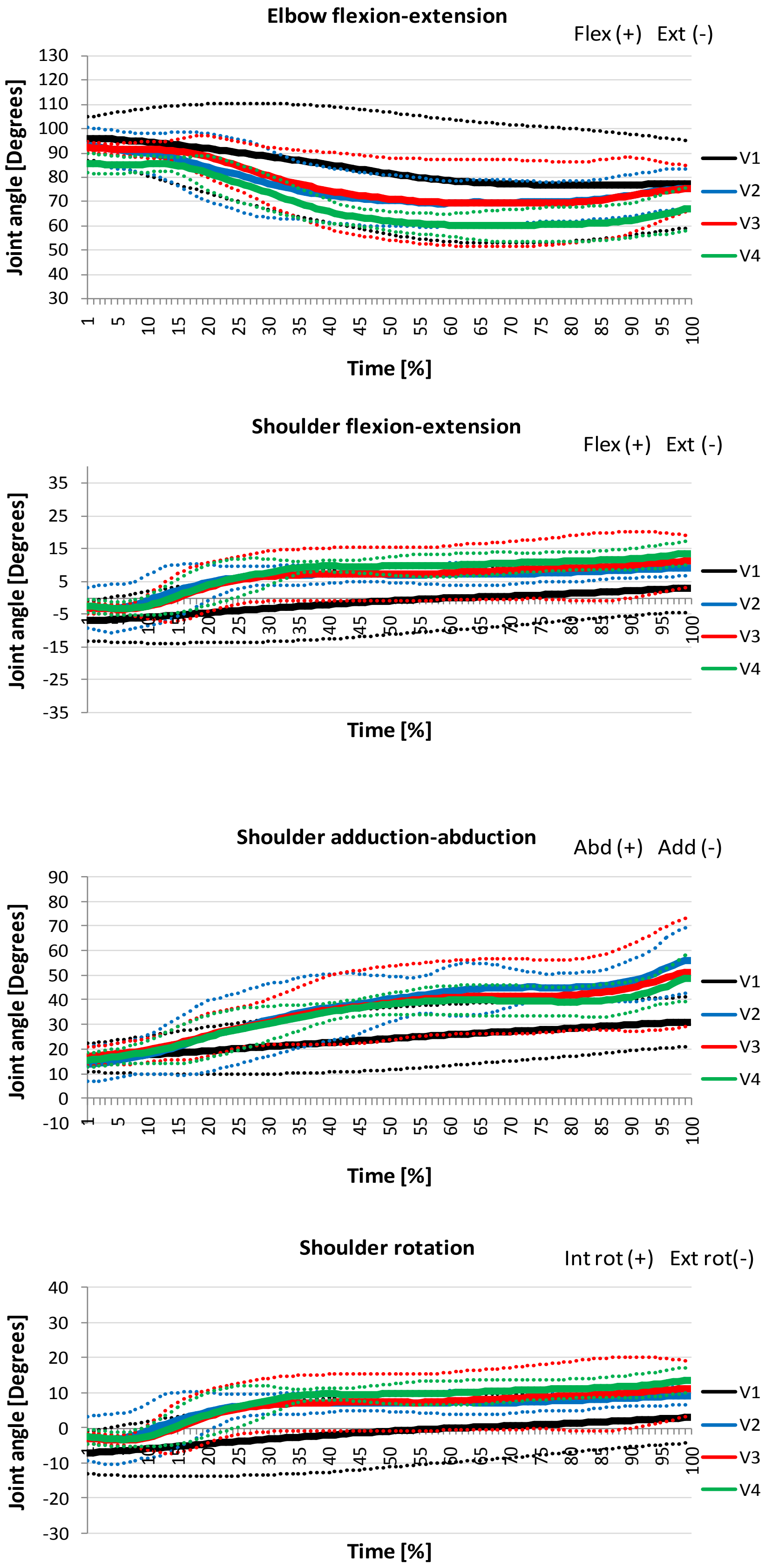



Figure 4. 11: Joint angle trajectories in reaching phase for Subject 1 across all visuomotor performance sessions. Time was normalised for illustration purpose. Thin dotted lines are upper and lower confidence intervals (CIs) of joint trajectories.

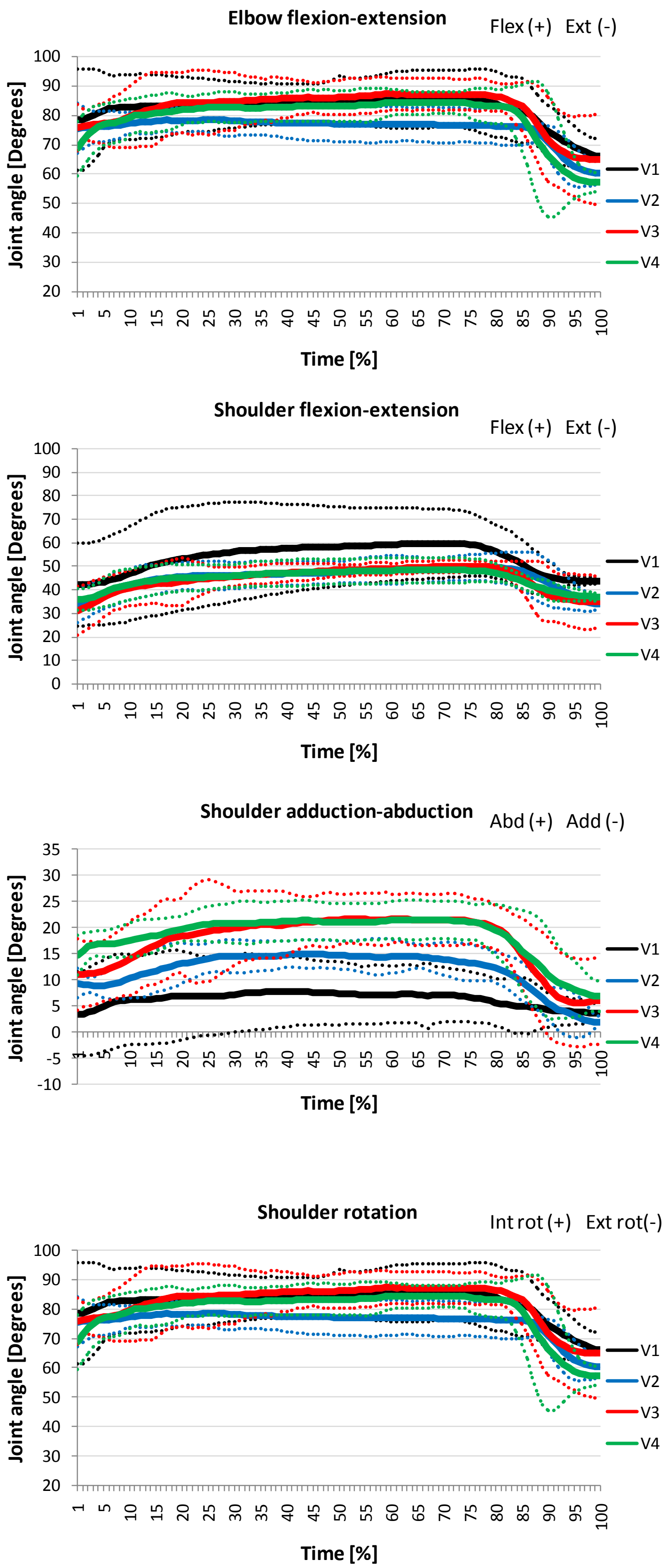



Figure 4. 12: Joint angle trajectories in manipulation phase for Subject 1 across all visuomotor performance sessions. Time was normalised for illustration purpose. Thin dotted lines are upper and lower confidence intervals (CIs) of joint trajectories.

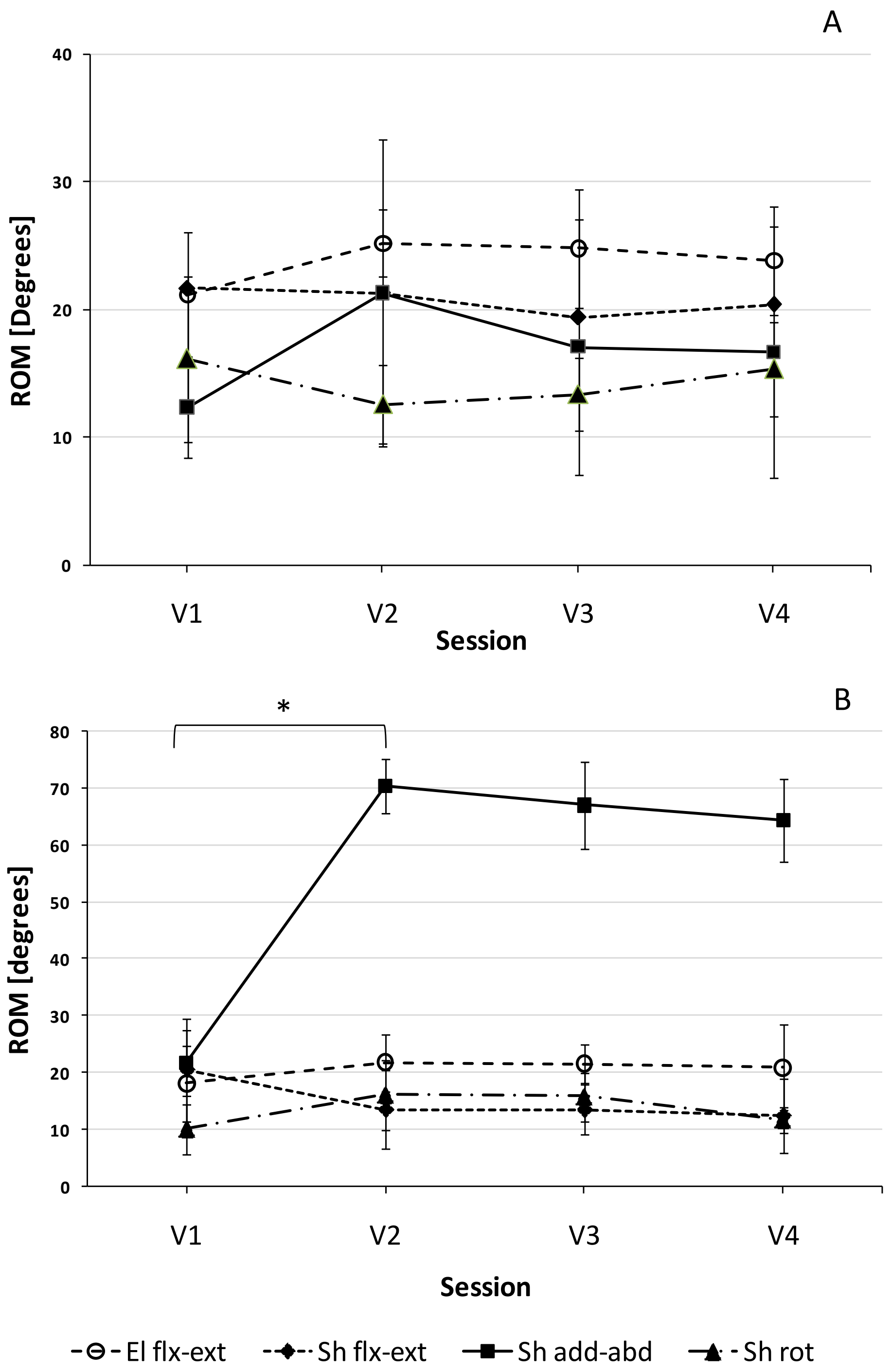



Figure 4. 13: Group means of the shoulder and elbow ROM across evaluation sessions during reaching (A) and manipulation phase (B). The asterisk indicates significance at $p < .05$ between the two sessions labelled by a square bracket.

#### *4.5.2.2. Acceleration variability*

As visualisation of warping of 3D acceleration trajectories is difficult, for illustration purposes examples of X axis accelerations from two trials before and after time warping in reaching and manipulation phase are shown in Figure 4. 14 and Figure 4. 15 respectively.

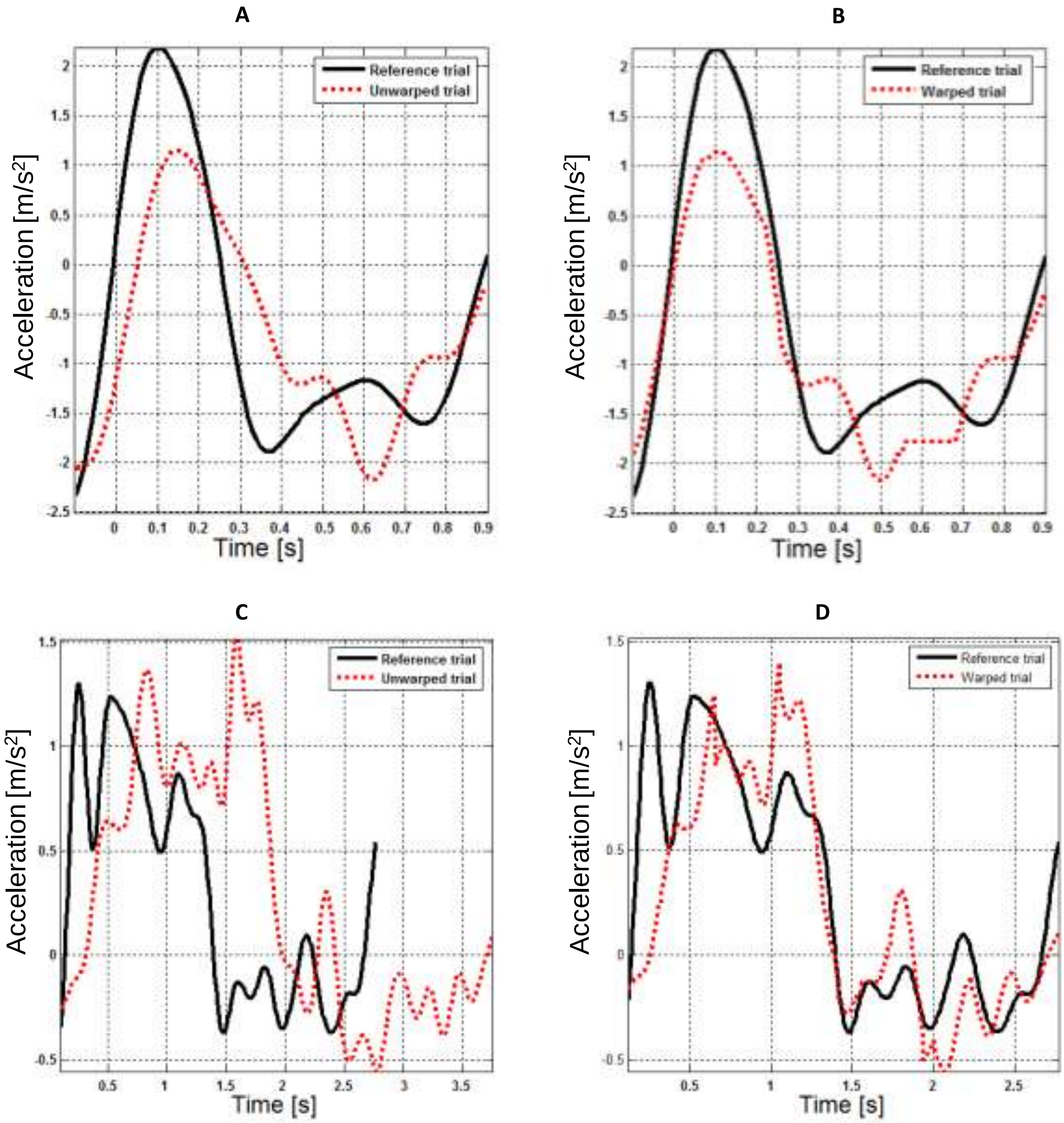



Figure 4. 14: Two acceleration trajectories from the X axis during reaching phase before (A) and after (B) time warping when the anatomical hand was used in V1, and before (C) and after (D) warping when the prosthesis was first used in V2 (data from Subject 1).

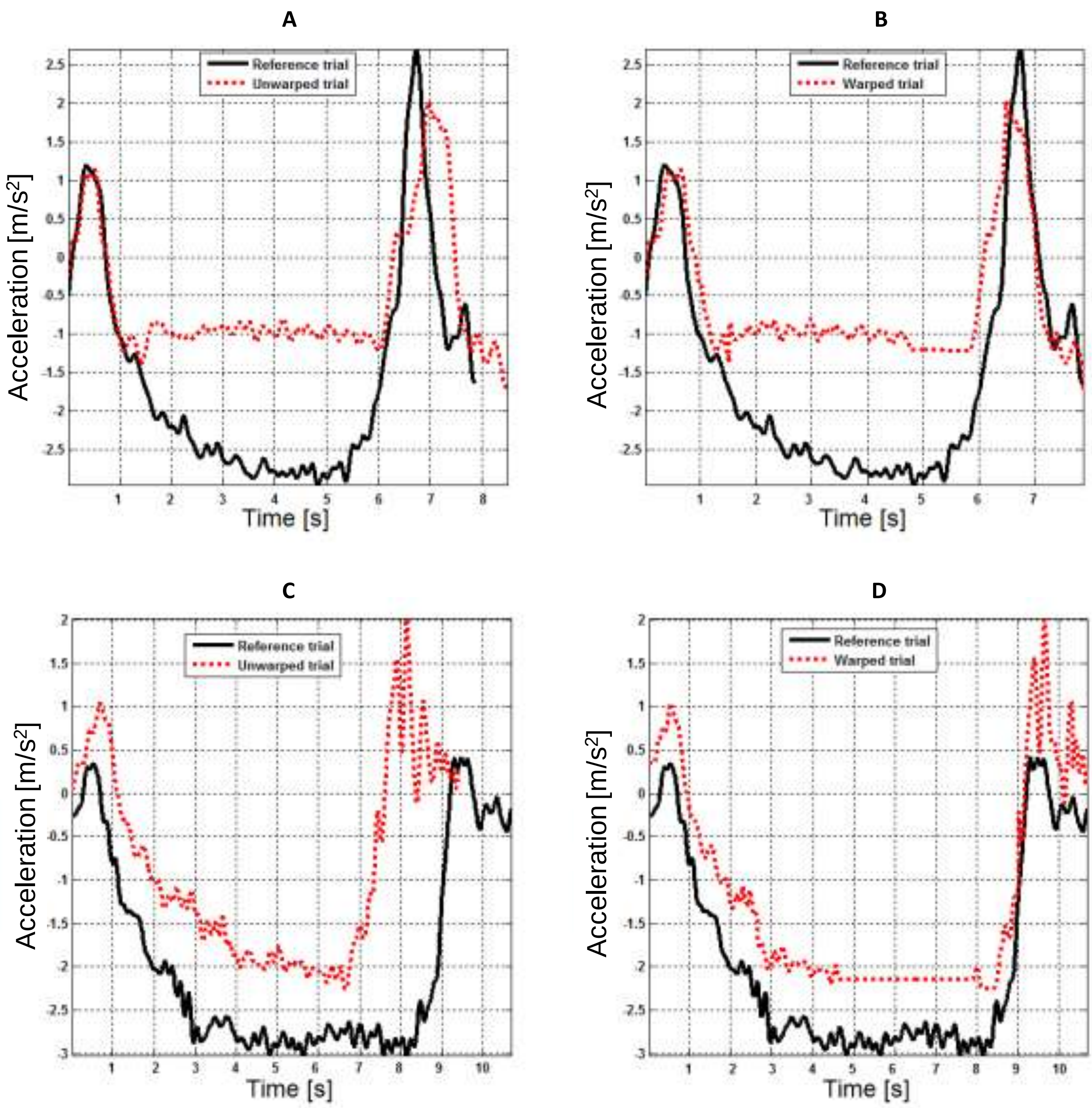



Figure 4. 15: Two acceleration trajectories from the X axis during manipulation phase before (A) and after (B) time warping when the anatomical hand was used in V1, and before (C) and after (D) warping when the prosthesis was first used in V2 (data from Subject 1).

Figure 4. 16 illustrates how group mean temporal and magnitude variability of 3D forearm-measured accelerations changed over the course of the study.

Temporal variability of acceleration signals increased significantly compared to baseline when the prosthesis simulator was first introduced (V2) by about six times in reaching ($F$ (1, 6) = 15.12, p<.05), and almost doubling in manipulation ($F$ (1, 6) = 6.28, p<.05). A decline in temporal variability was observed in both phases with repeated use of the prosthesis simulator (V4), however, this was significant only for the reaching phase ($F$ (1, 6) = 11.82, p<.05).

The magnitude variability declined in reaching when the prosthesis was introduced in V2 and a further slight decline over practice to use the prosthesis. In manipulation, magnitude variability increased slightly at V2 and then decreased at V3 and V4. In contrast to temporal variability, the main effect of session on RMSE was not significant during reaching ($F$ (2, 12) = 0.49, p>.05) and neither during manipulation ($F$ (2, 12) = 3.29, p>.05).

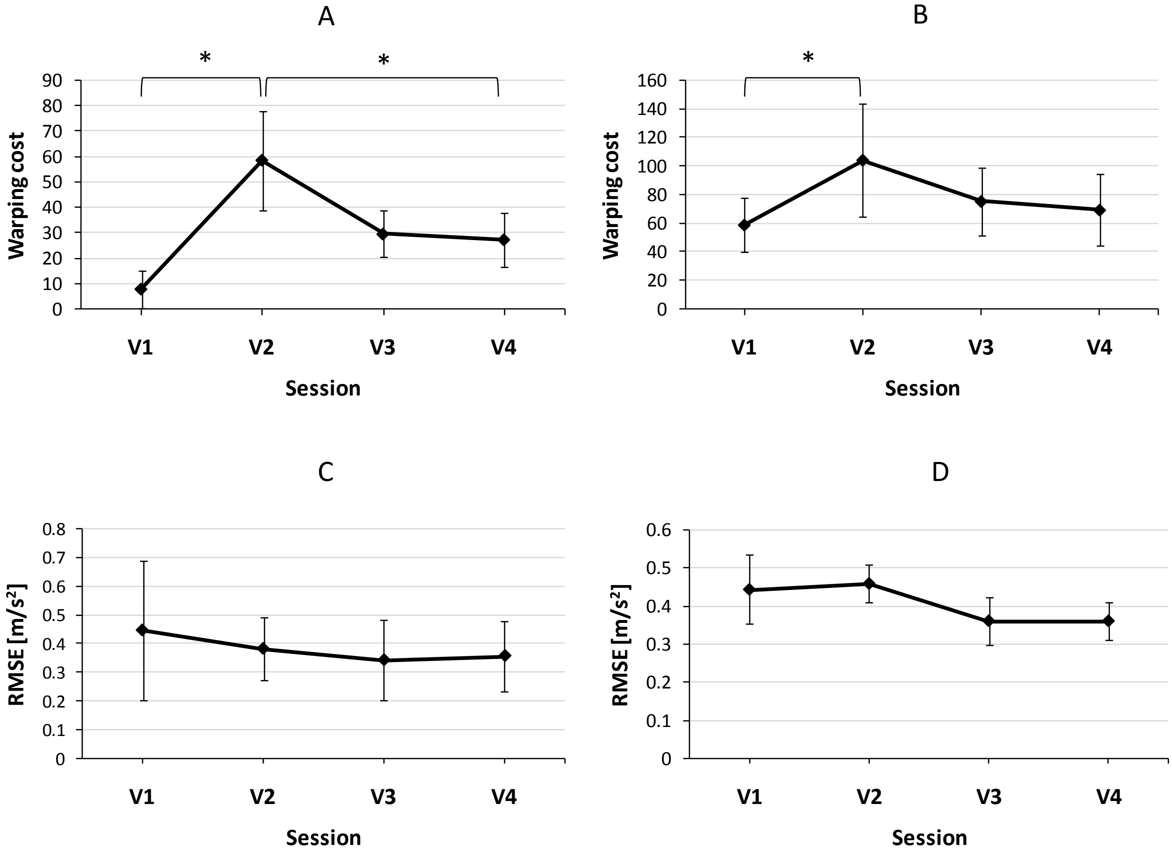



Figure 4. 16: Group means of temporal variability in reaching (A) and manipulation (B), and magnitude variability in reaching (C) and manipulation (D) in the forearm-measured accelerations across the visuomotor performance sessions. The asterisk indicates significance at p < .05 between the two sessions labelled by a square bracket.

#### *4.5.2.3. Movement velocity and hand aperture during the reaching phase*

Figure 4. 17 shows examples of forearm velocity (measured at the wrist joint centre) and hand aperture profiles for the visuomotor performance sessions in a representative subject. Forearm velocity data and hand aperture profiles for all subjects are listed in Appendix H.

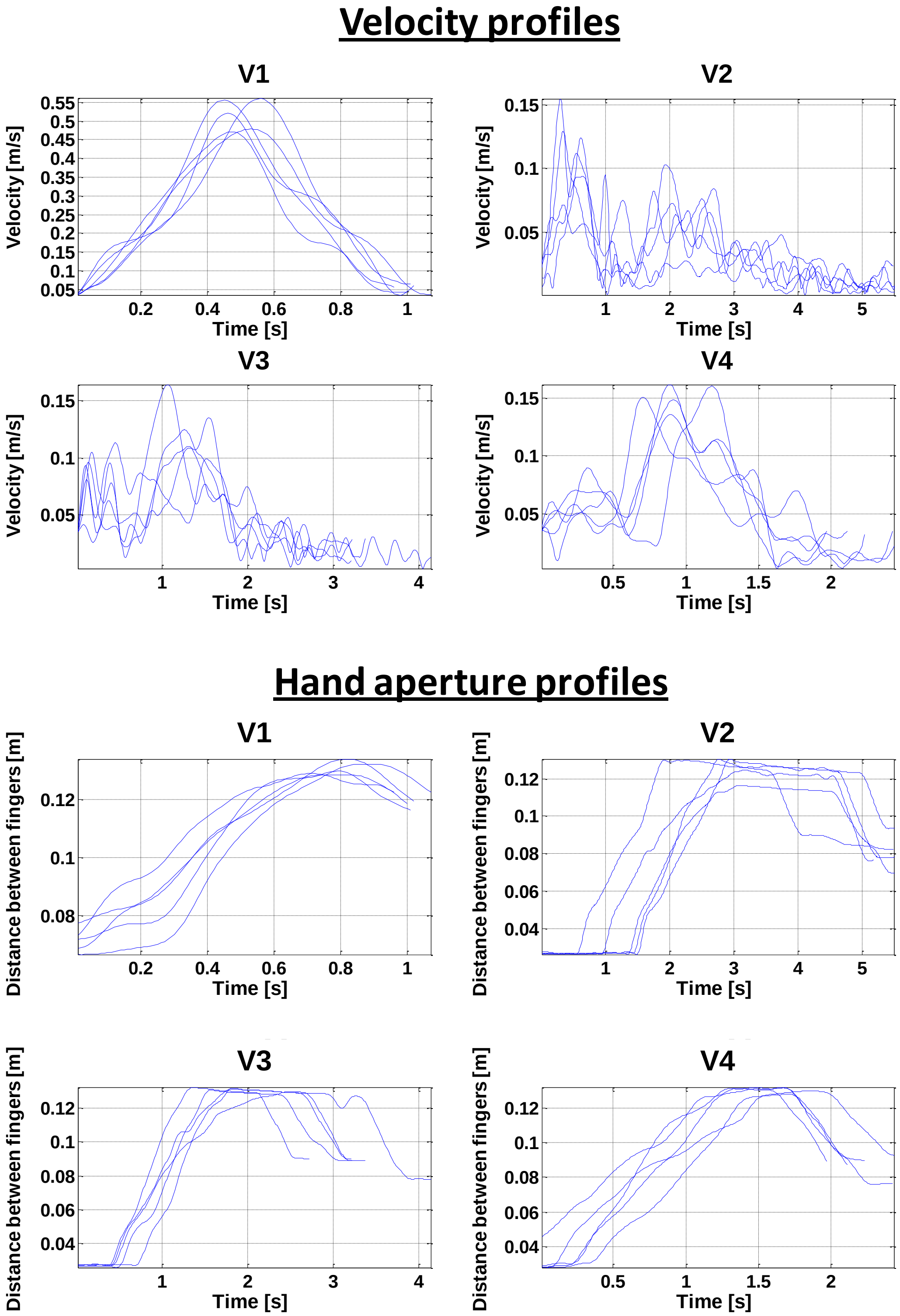



Figure 4. 17: Examples of 5 trials wrist's velocity and hand aperture profiles for all visuomotor performance sessions for Subject 1.

In Figure 4. 18, the changes to peak velocity and time to peak velocity over V sessions are illustrated. A significant effect of session was found on peak velocity ($F$ (1.08, 6.48) = 35.35 $p<.05$). Velocity appeared to drop considerably with introduction of the prosthesis (V2) and this was found to be significant ($F$ (1, 6) =36.65, p<.05). A slight but significant improvement occurred after training (from 0.16 m/s in V2 to 0.18 m/s in V4) ($F$ (1, 6) = 8.80, p< .05).

Likewise, a significant main effect of session was shown on time to peak velocity ($F$ (2, 12) =8.81, p<.05). Time to peak velocity was found to significantly increase when introducing the prosthesis in V2 ($F$ (1, 6) =20.15, p<.05).

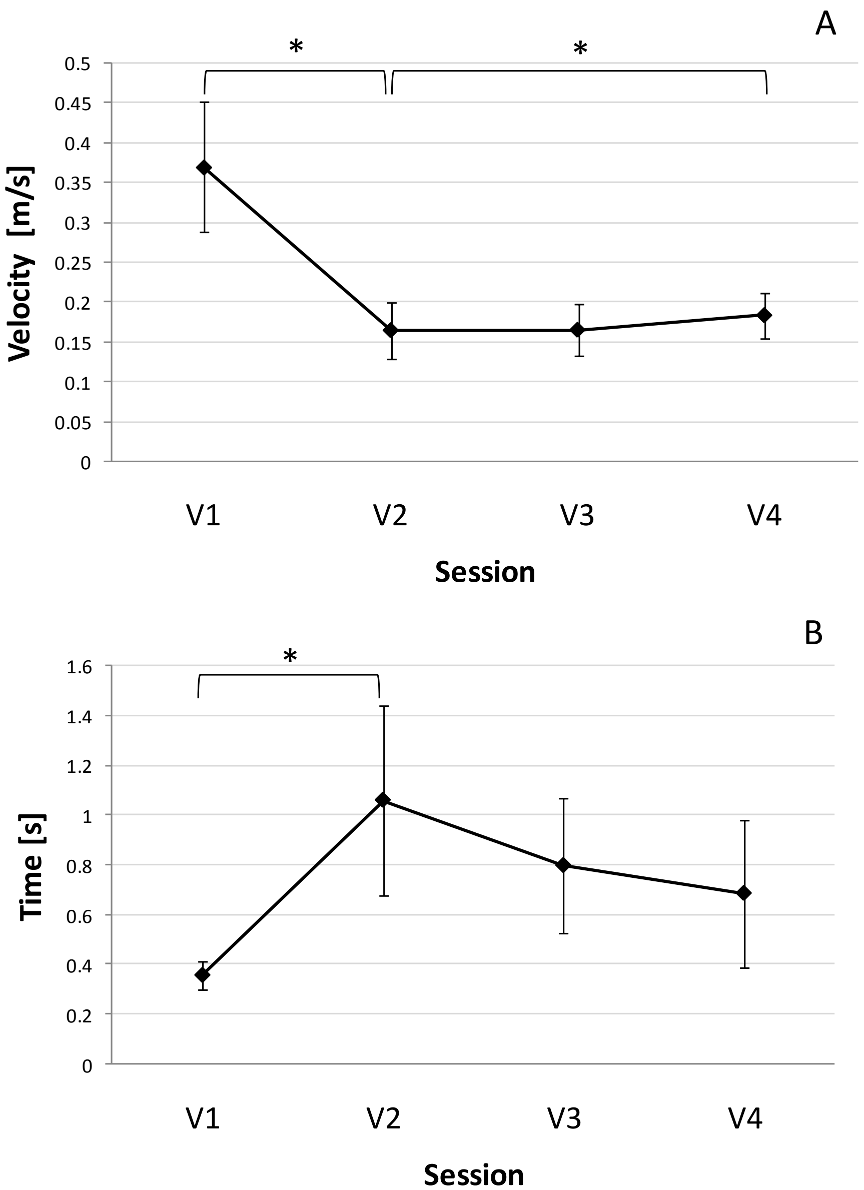



Figure 4. 18: Group means of peak velocity (A) and time to peak velocity (B) across all visuomotor performance sessions. The asterisk indicates significance at p < .05 between the two sessions labelled by a square bracket.

Figure 4. 19 illustrates how time to peak aperture during the reaching phase changed over sessions. The main effect of session was significant with regard to time to peak aperture ($F$

(1.28, 7.68) = 19.51, p<.05). Time to peak velocity increased when introducing the prosthesis (V1 to V2) and this increase was significant ($F$ (1, 6) = 34.60, p<.05). With learning to use the prosthesis (V2 to V4) a significant decrease in time to peak velocity was found ($F$ (1, 6) = 4.95, p<.05).

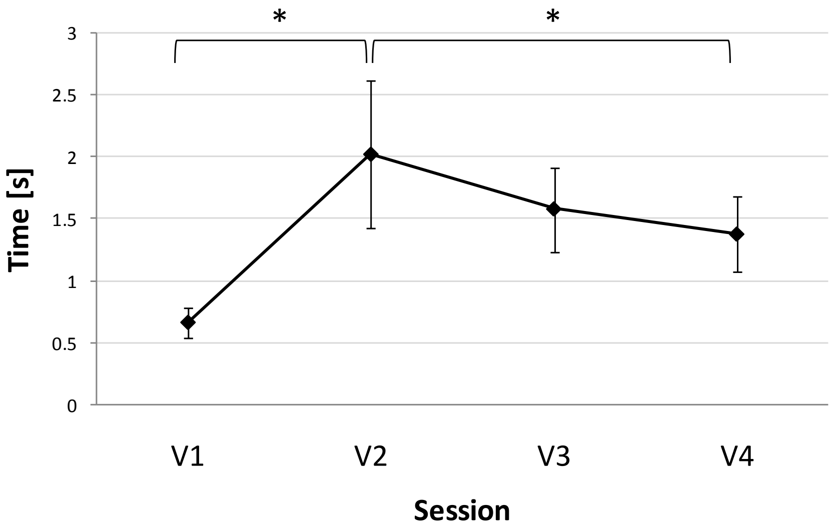



Figure 4. 19: Group means of time to peak aperture across visuomotor performance sessions. The asterisk indicates significance at p < .05 between the two sessions labelled by a square bracket.

### *4.5.3. Gaze data*

Figure 4. 20 and Figure 4. 21 represent examples of gaze sequencing across all visuomotor performance sessions in a representative subject during reaching and manipulation. The entire gaze sequence data for all subjects are in Appendix I.

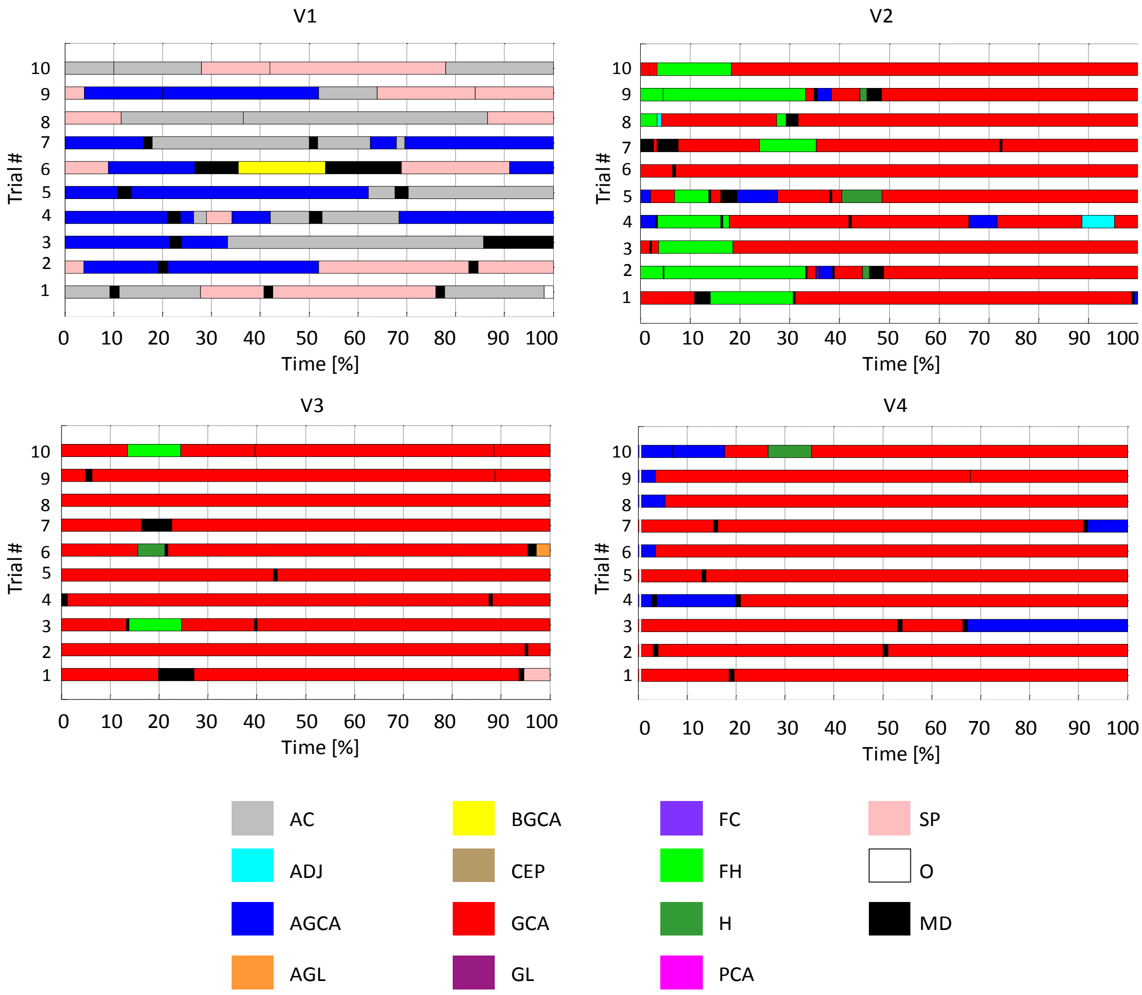



Figure 4. 20: Gaze sequence of all 10 trials during the reaching phase in all visuomotor performance sessions for Subject 1. The trial number is represented on the vertical axis. The horizontal axis represents the task duration normalised to 100%. The gaze fixation sequence in a given trial is presented in a stacked bar in which each coloured segment denotes a gaze fixation at a particular AOI, the length of each coloured segment corresponds to the duration of the fixation at the AOI

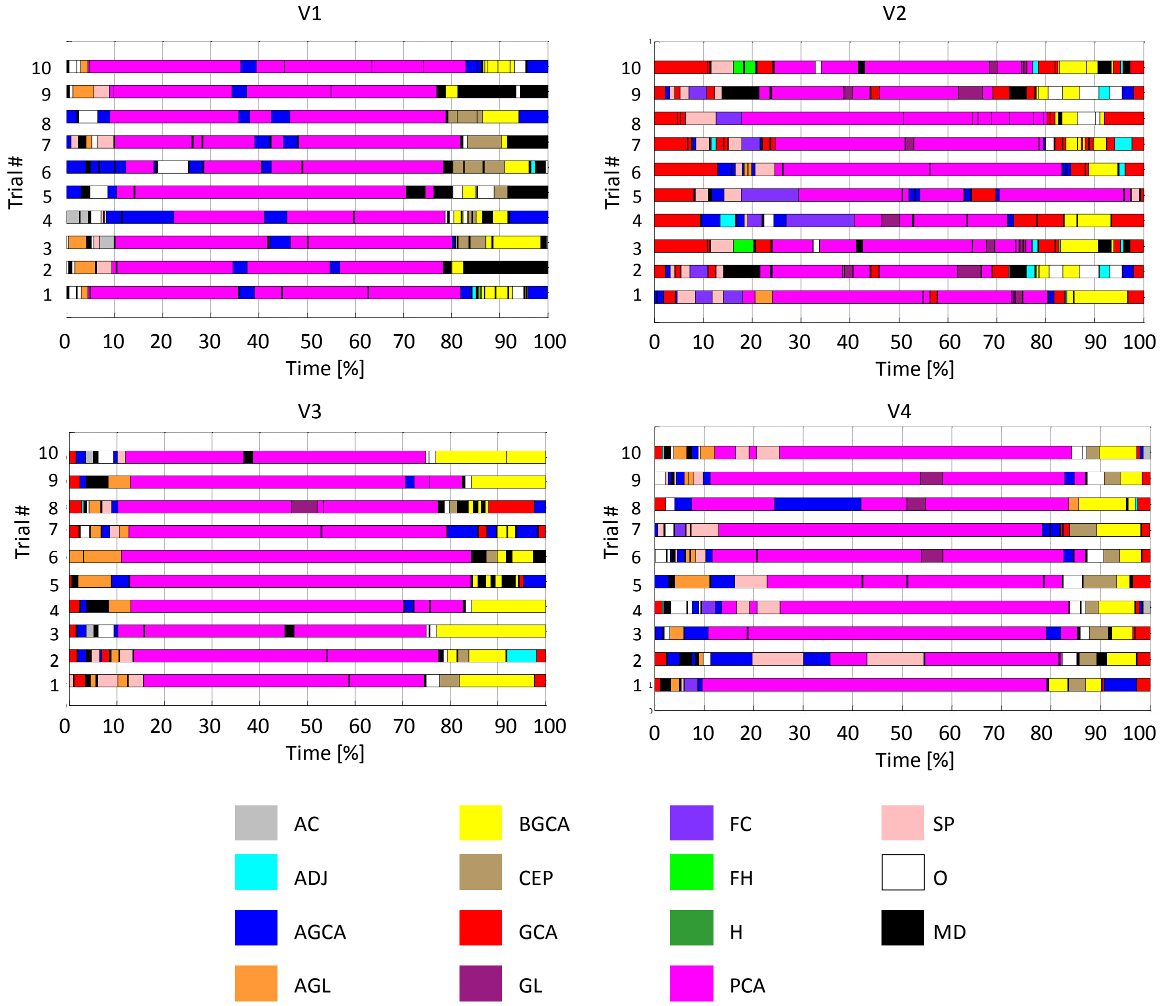



Figure 4. 21: Gaze sequence of all 10 trials during the manipulation phase in all visuomotor performance sessions for Subject 1. The trial number is represented on the vertical axis. The horizontal axis represents the task duration normalised to 100%. The gaze fixation sequence in a given trial is presented in a stacked bar in which each coloured segment denotes a gaze fixation at a particular AOI, the length of each coloured segment corresponds to the duration of the fixation at the AOI.

The group means of the number of transitions between AOIs during both the reaching and manipulation phases across visuomotor performance sessions are illustrated in Figure 4. 22. In general, subjects made fewer transitions when they used their anatomical arm to perform the task. In addition, fewer transitions were required after the training period (V4) as compared to before training (V2). Statistical analysis showed a main effect of session on number of transitions in reaching ($F$ (2, 12) =4.22, p <.05) and in manipulation ($F$ (2, 12) = 9.81, p< .05). When comparing pairs, only introducing the prosthesis (V1 vs. V2) significantly affected the number of transitions in reaching (($F$ (1, 6) = 25.14, p <.05) and manipulation ($F$ (1, 6) = 20.70, p <.05).

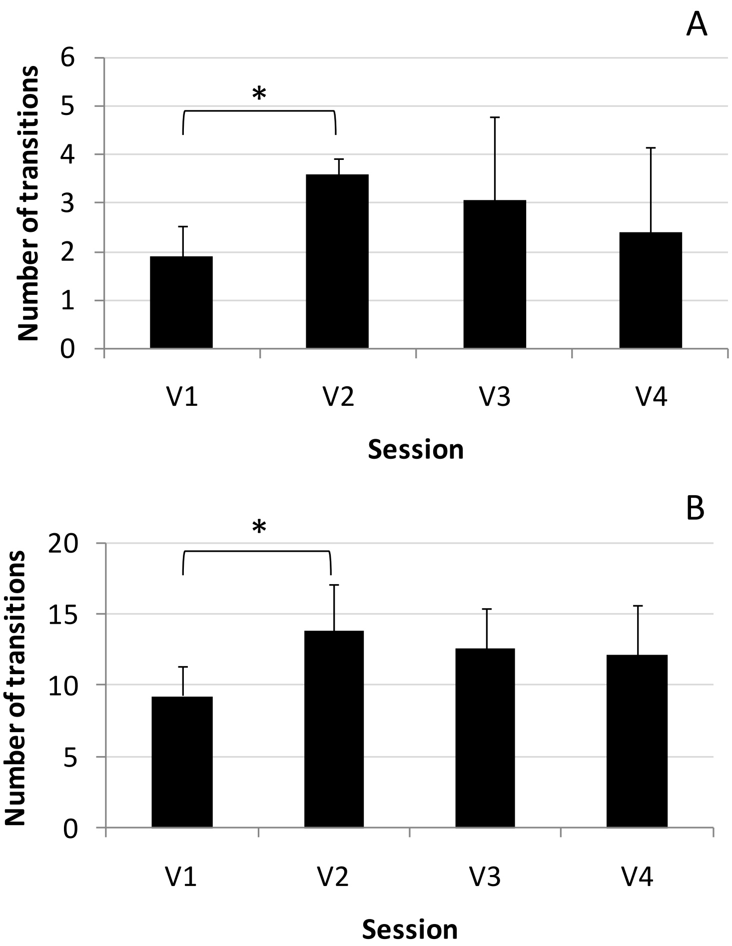



Figure 4. 22: Group means of number of transitions between AOIs during reaching (A) and manipulation phase (B) across visuomotor performance sessions. The asterisk indicates significance at $p < .05$ between the two sessions labelled by a square bracket.

Figure 4. 23 and Figure 4. 24 show the group means of normalised gaze duration at each AOI across visuomotor performance sessions for the reaching phase and manipulation phase, respectively.

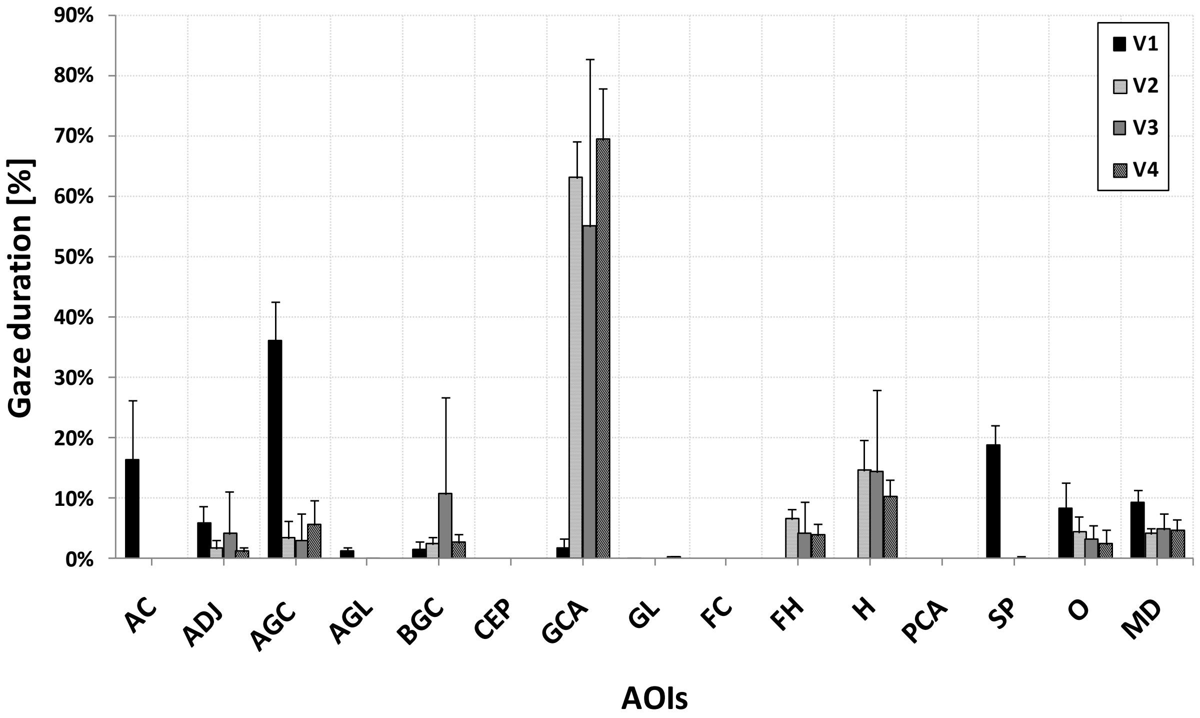



Figure 4. 23: Group means of normalised gaze duration at AOIs during the reaching phase across visuomotor performance sessions.

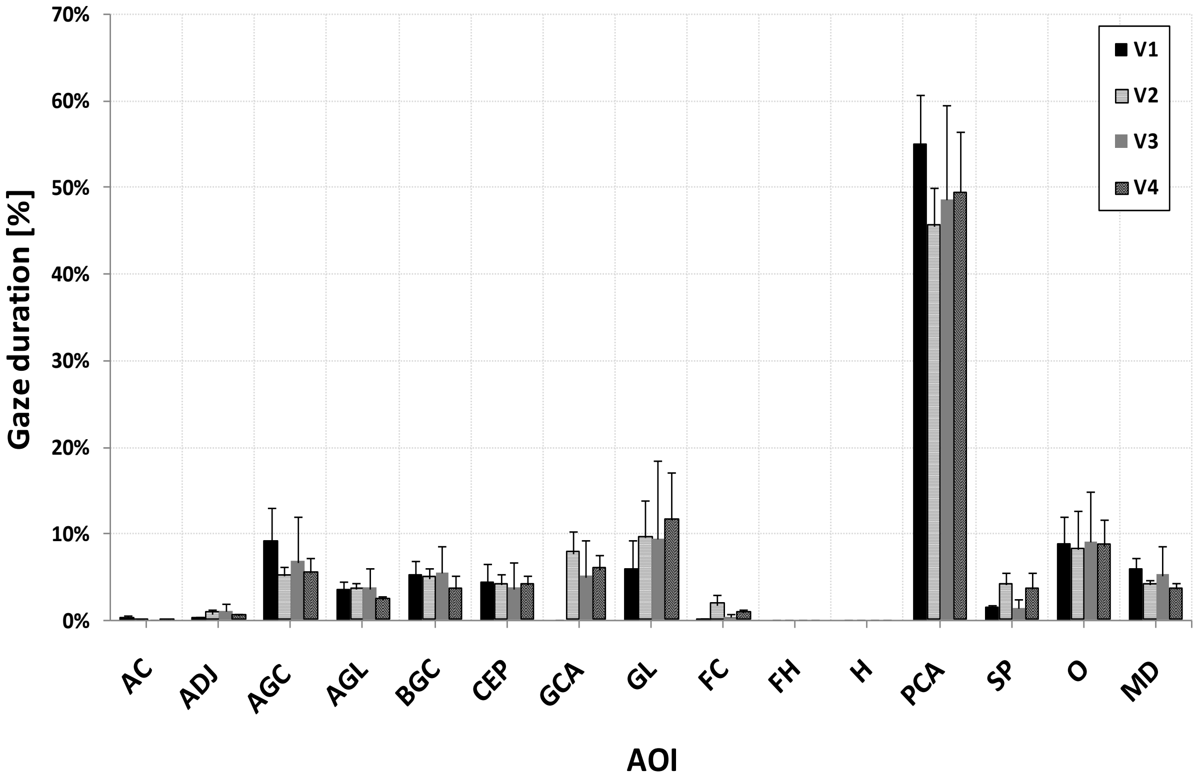



Figure 4. 24: Group means of normalised gaze duration at AOIs during the manipulation phase across visuomotor performance sessions.

## 4.6. Discussion

### *4.6.1. SHAP scores and task completion time*

Time to complete a task is one of the classical indicators of functional ability and is used in many outcome measures, such as the Nine-Hole-Peg test (218), Box and Block test (107), and SHAP (25). In this study, time to perform tasks, whether indicated indirectly by SHAP scores, or directly calculated for the manual task, increased with introducing the prosthesis and reduced with training (Table 4. 4 and Table 4. 5). From Figure 4. 10, it can be seen that the decrement in task duration within-session is steeper in V2 than in other sessions; implying that, although on average subjects completed the task slower in V2 (Table 4. 4), they were learning at a faster rate. This behaviour is also reflected in the temporal variability data, as will be discussed below.

### *4.6.2. Kinematic data*

#### *4.6.2.1. Joint angles and ROMs*

The carton location and orientation on the table allowed reaching and grasping with elbow and shoulder flexion and minimal wrist flexion and shoulder abduction (Figure 4. 13-A). When using the anatomical hand, an average of $12^0$ of shoulder abduction ROM was required to reach and grasp the carton; with a prosthesis, an additional $9^0$ was required. Over training only a small but steady decrease in average shoulder abduction ROM was observed during the reaching phase. Statistical analysis revealed no significant main effect of sessions or significant interaction between sessions and ROM.

In the manipulation phase, only shoulder adduction-abduction ROM appeared to be influenced by the introduction of the prosthesis. More than a threefold increase of shoulder adduction-abduction ROM was observed (Figure 4. 13-B), and this difference was found to be significant. The mean value dropped slightly between V2 and V4 but this was not significant. From visual observation of the task, excessive shoulder abduction was needed for pouring water from a carton. Pouring would normally involve substantial active wrist pronation (219, 220) which is greatly restricted when the prosthesis was introduced. This lack of active wrist movement in the prosthesis appeared to be compensated for through an increase in shoulder abduction. King et al found a similar effect on shoulder motion in the coronal plane when an upper limb orthosis which also greatly restricted wrist motion was used (221).

#### 4.6.2.2. *Temporal and magnitude variability*

As the manipulation phase is a complex sequence of sub-events, it is difficult to draw any clear conclusions from the variability data and hence this discussion will primarily focus on the changes seen in the reaching phase. Introducing the prosthesis in session V2 resulted in a dramatic and significant increase in temporal variability compared to baseline (V1) (Figure 4. 16-A, Figure 4. 16-B). As Table 4. 4 and Figure 4. 10 show, unsurprisingly subjects were very slow in reaching especially during their first attempts with the prosthesis in V2, and mean reaching time decreased by more than 30% from the first to the last attempt in the session. From Figure 4. 17, it was also noticed that there were moments in V2 at which subjects paused in their reach (possibly to activate the hand). High temporal variability in V2 is therefore a result of both the steady reduction in task completion time within the session and high variability in certain kinematic aspects (as shown by the high variability in forearm velocity illustrated in Figure 4. 17). The high variability in V2 appears to fit with the first learning stage according to Fitts and Posner's three-stage model of motor learning, a stage associated with high variability in performance during which subjects learn the requirements of the task and start to develop strategies (222). Following the first two SHAP sessions with the prosthesis, the temporal variability showed a marked decrease at V3 to a level still three times that seen in anatomical reaching; variability decreased further by V4. This may suggest subjects were in the second stage of motor learning according to the Fitts and Posner model during which the most suitable control strategy has been selected and skills are being refined. The third stage of Fitts and Posner model is achieved when the performance becomes autonomous (222). Autonomous performance, at least in the reaching phase, is likely to be associated with ballistic and smooth movement trajectories as seen when the anatomical arm was used. Despite the improvement, arm movement remained clearly erratic and slow.

It was also expected to see a similar pattern in the magnitude variability data. However, reaching showed no significant change between V1 and V2 and neither between V2 and V4 (Figure 4. 16-C). This was surprising as the prosthesis has reduced DoF compared with the anatomical limb and hence it was expected to see a decrease in variability on first use of the prosthesis associated with a more constrained spatial trajectory. One possible explanation is that when using the anatomical arm, starting with the palm of the hand flat on the table, the reaching movement also involved a pronation movement to re-orient the hand for grasping, which would be associated with a certain degree of variability. When first using the prosthesis a trial and error strategy (reflected in the velocity plots (Figure 4. 17) may have led to an increase in magnitude variability. This effect may have been offset by the consequences of the initial prosthesis hand orientation (it was pre-oriented to achieve the grasp (the hand was always fixed to the mid-supination-pronation position)) resulting in there being little benefit to varying this relatively straight and simple trajectory. The magnitude variability data observed during manipulation was also difficult to explain. It is possible that a similar trade off occurred at V2 and the subsequent drop off at V3 and V4 were a result of the constrained choices in trajectories becoming the dominant influence.

It therefore appears that the magnitude variability in reaching in the used ADL task is largely invariant to the introduction of the prosthesis or training. There appears to be some effect on magnitude variability with practice, but this is difficult to explain and should be treated with caution. In contrast, the variability of timing of movement is greatly influenced by both the introduction of the prosthesis (reaching and manipulation) and training (reaching only).

#### *4.6.2.3. Forearm velocity and hand aperture characteristics in reaching*

In reaching, forearm velocity measured at the wrist joint centre showed an asymmetrical bell-shaped profile for all subjects at V1. Peak velocity averaged 0.36 m/s, and was reached at around 35% of the reach movement time (see examples in Figure 4. 17and Figure 4. 18-B). This trend has been observed in many previous studies (e.g. (223, 224)). Despite the variation in the peak velocity between subjects at V1, time to peak velocity was highly consistent (see Figure 4. 18-B), and consistent with an earlier study by Paulignan et al (225). Also, consistent with the early findings of Jeannerod (27), peak hand aperture occurred during the first half of the deceleration phase and the hand aperture profile resembled an asymmetrical curve (see examples of V1 in Figure 4. 17), skewed to the right, with its peak occurring consistently after peak velocity (at around 60% through the reach). Finally, as expected (27), the hand began to open at or few ms after the onset of movement (see V1, for example in Figure 4. 17).

At V2 on the introduction of the prosthesis, the bell-shaped velocity profile was severely distorted and the peak amplitude dropped by about half, as can be seen in Figure 4. 17 and Figure 4. 18-A. Time to peak velocity increased from 0.38 s to over 1s. These changes to peak amplitude and time to peak velocity were found to be significant.

Hand aperture profile showed one or more plateaus when the hand reached the maximum aperture. The presence of more than one plateau occurred when the control of the hand was lost and it accidentally closed during movement towards the carton. Time to first peak aperture was reached about 2 s from the onset of the movement in V2, around 40% through the reaching phase.

Over the course of practice, although the velocity profile did not return for a normal bell-shaped curve as seen examples in Figure 4. 17, a general improvement was observed: there was a general tendency to greater consistency with fewer velocity peaks. An increase in the amplitude of peak velocity and a decrease in time to peak velocity were observed with practice. However, with practice, only changes to peak velocity (but not the time to peak velocity) were found to be significant. Improvement in time to peak aperture was also observed; as it declined steadily over the course of training (Figure 4. 19). This improvement was found to be significant.

From Figure 4. 17 it is notable that in V1 the arm and hand motion were closely and smoothly coupled as previously described by Jeannerod (27). In session V2, this stereotypical behaviour changed dramatically, although trends towards re-establishing similar behaviour were evident in V3 and V4. For example, the maximum hand aperture was frequently achieved before reaching the peak velocity. In some cases, subjects started to open the hand even before starting to reach towards the carton, a behaviour that has been reported previously (8).

In a study of established users of threshold-controlled myoelectric prostheses by Bouwsema et al (8), and in line with the findings of this chapter, a multi-peaked wrist velocity profile was observed when reaching to grasp objects with a trans-radial prosthesis. Additionally, Bouwsema et al reported hand aperture profiles with an extended plateau corresponding to maximum hand aperture similar to what it was observed in the present study. Interestingly, this characteristic of hand aperture was also reported in an established body powered trans-radial prosthesis user (5). Wing and Fraser related the existence of plateau to the reliance on vision to control the motion with the disruption of the proprioception, so users tend to delay hand closing until the hand is in the vicinity of the object. This may also be a partial explanation for myoelectric prosthesis users in the present study, but the constant operation velocity of the hand motor of the hand is also likely to contribute.

It is likely that the proprioceptive deficit on the introduction of the prosthesis led to the similarities in characteristics of arm and hand movements during reaching to grasp with those seen in studies of both mechanical grabber users and deafferented subjects. For example, in line with the other studies (33, 42, 64, 66), subjects in this study reached to grasp objects with lower peak velocity than with their contralateral intact limb, and the bell-shaped wrist velocity profile while reaching was also distorted. However, the wrist velocity was found to be more erratic in prosthesis users than in subjects using a grabber (64, 66), or in studies of deafferented subjects (33, 42). Generally, the grip aperture in studies of all three populations (prosthesis users, users of mechanical grabbers and deafferented subjects) was also found to be characterised by a prominent plateau.

Notably, although many temporal and spatial characteristics of the investigated variables indicated the difference between prosthetic and anatomical hand use, temporal characteristics were found more often indicative of improvement with practice (from V2 to V4).

### *4.6.3. Gaze data*

With regard to gaze behaviour, the gross changes to gaze behaviour as shown from number of transitions between AOIs to complete the task and the duration spent at each AOI will first be discussed. Changes to gaze duration will be discussed with particular focus on those AOIs that either showed major changes in gaze duration between V1 and V2 and/or between V2 and V4. Finally, the idea of aggregating functionally relevant AOIs will be introduced in order to pinpoint more clearly the effects of introducing the prosthesis and of learning to use the prosthesis on gaze behaviour.

As mentioned earlier in the Introduction, when performing a familiar upper limb task gaze usually follows a particular characteristic routine path involving fixation at certain key AOIs, and thus the number of transitions between AOIs is normally low. In contrast, for difficult and/or novel tasks, gaze behaviour tends to be erratic, with more frequent transitions between AOIs (68, 226). This more erratic behaviour may reflect a lack of familiarity / routine for extracting relevant visual information leading to a reduction in the efficiency with which relevant visual feedback is obtained (201). With practice, the number of transitions is reduced and the search strategy becomes more consistent. For example, Vickers noticed that expert golf players in comparison to naive players produced fewer transitions between different objects in the scene ahead (226). In another study Law et al found that experts in using a laparoscopic tool tended to maintain a clearly defined and hence stereotypical gaze fixation strategy, whereas naive users exhibited varied gaze fixation strategies (68). The results of this chapter agreed with the general patterns reported in the literature. There were significantly fewer transitions between AOIs in V1 compared to V2 in both the reaching and manipulation phases (Figure 4. 22). Over the course of practice the number of transitions continuously decreased, however, the level of reduction at V4 was fairly modest and statistically non-significant.

In the next section, the results analysed in terms of the distribution of the duration of fixations across the AOIs will be discussed.

#### *4.6.3.1. Reaching phase*

In line with previous research (49), during reaching with the anatomical hand subjects did not generally focus either on the hand or its associated area "Following Hand" (Figure 4. 23. Instead, subjects tended to fixate their gaze at the areas of relevance to the subsequent action ("look-ahead fixations" (50)), notably at "Above Grasping Critical Area" (AGC), "Spout" (SP) and/or "Above Carton" (AC) (examples of gaze sequence in Figure 4. 20) which may indicate planning for subsequent parts of the task, i.e. preparing to pour from the carton. In fact, in cases where fixation at the GCA is seen, it is generally at the beginning of reaching (see gaze sequence of all trials in Appendix I), followed by fixation at AGC, SP and/or AC. This later observation agrees with the findings of Johansson et al in their study (38). In this study, reaching to grasp a bar, with the intention to transfer it to another place, was associated with fixation at grasping points while reaching and a subsequent "look-ahead fixation" at the other side of the bar at the end of reaching and before/at the moment of establishing the grasp (38). Such a gaze sequence does not emerge when the intention is solely to reach and grasp the object with no further action (186, 187).

The so-called "planning ahead" strategy was also noted at the end of the reaching phase: subjects, when first grasping the carton, briefly fixated "Above Glass" (AGL), or less frequently "Glass" (GL); i.e. AOIs that are relevant to planning the movement to be performed in the subsequent phase. Even during initial grasping of the carton (once the contact was achieved), which may involve corrections to the executed movement and hand orientation through a feedback control strategy, such feedback appeared to be mainly provided through channels other than vision, thereby allowing "looking ahead" to plan the subsequent action (50).

In contrast to reaching with the anatomical hand, in V2 prosthetic reaching was mostly initiated with gaze fixation at the GCA and in some subjects (e.g. Figure 4. 20) with occasional fixations of the prosthetic hand. During reaching, subjects most often pursued the prosthetic hand and/or flickered between the hand and the GCA. The attention given to the

GCA may indicate planning initially, before the hand is in the vicinity of the carton, however later on in reaching it can be argued that its role is to guide the hand-carton interaction. Attention given towards the hand, and "Following Hand" is probably associated with concern regarding the hand configuration and location. Attention to all these areas (GCA, Hand, and Following Hand) largely precluded the subjects from planning ahead for the manipulation phase.

It appeared that with practice the duration of the fixation at the GCA during reaching increased slightly, probably as a result of a shorter fixation on the hand area. Although such a change in the gaze behaviour may reflect the ability of subjects to incorporate the prosthesis into the internal kinematic model of the forearm, interaction with the object remained attentionally demanding.

From the discussion above, it is possible therefore to define two main functions that the gaze serves during reaching to grasp in the used ADL task:

1. Planning ahead actions, which seem to be mainly observed in V1 and may be characterised by:
    - Fixations at Above GCA, Spout and Above Carton AOIs to plan the early stages of manipulation, including transferring and concurrently tilting the carton. These will be referred to as "Top of carton" AOIs;

    - Fixation at Glass and Above Glass AOIs to plan the pouring action. These will be referred to as "Glass related" AOIs.

2. Guiding actions which seems to be mainly observed in V2-V4 and may be characterised by:
    - Fixation at Hand and Following Hand AOIs to guide the hand during transporting the forearm towards the carton and to monitor its state (i.e. opening, closing, static). These will be referred to as "Hand related" AOIs.

    - Fixation at GCA to guide the hand-object interaction. Fixation at Below GCA and Adjacent to GCA can be also considered related to this function in reaching as both AOIs are adjacent to the GCA and it is not clear that fixation at these areas would serve any other functional purpose. It will be referred to these AOIs as "GCA related" AOIs.

Combining AOIs in this way may provide a clearer way of illustrating gaze behaviour in this task. Figure 4. 25 shows the fixation duration during reaching after combining relevant AOIs.

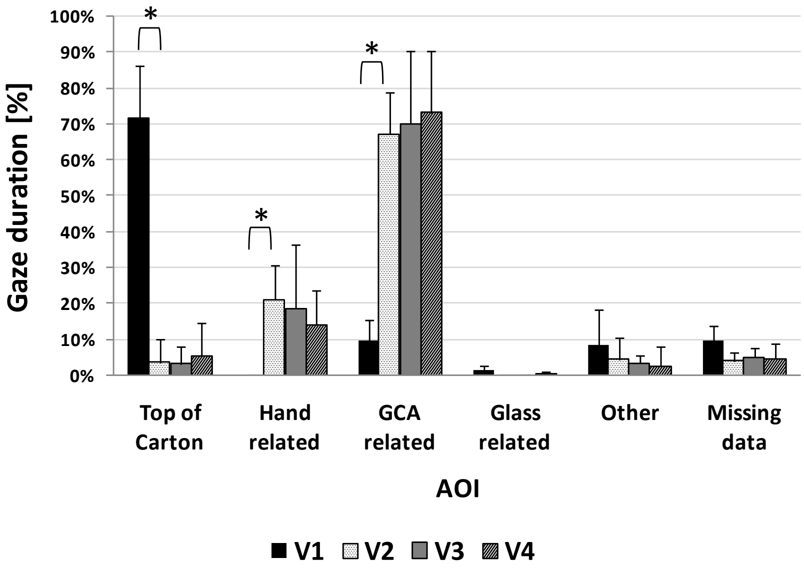



Figure 4. 25: Group mean duration for combined AOIs in reaching phase. The asterisk indicates significance at $p < .05$ between the two sessions labelled by a square bracket.

From Figure 4. 25, it is clear that planning ahead was severely affected when the prosthesis was first introduced in V2, whether to plan the early stage of manipulation or to plan pouring. It is also clear that attention to guide the hand towards the carton (Hand-related AOI) and to guide the grasp (GCA-related AOI) increased dramatically in V2.

Over practice, planning improved to a limited degree. However, less attention was devoted to guiding the hand during transport and more attention was given to monitoring the grasp. It appears that there was a reciprocal relationship between these two areas. It was also interesting to observe the re-emergence of Glass-related AOI at V4, although this effect was extremely small. Statistical analyses showed significant difference only between V1 and V2 for "Top of the carton" ($F$ (1, 6) = 86.60, p<.05), "Hand related" ($F$ (1, 6) = 291.34, p<.05) and "GCA related" AOIs ($F$ (1, 6) = 39.83, p<.05), (see Appendix E for detail).

#### 4.6.3.2. *Manipulation phase*

As in reaching, vision also serves various different functions during manipulation including planning, guiding, and monitoring actions (49). However, and mainly due to the complexity of the manipulation phase in the chosen task, fixation at a particular AOI may serve different functions depending on where in the manipulation phase it occurs. Hence, it is difficult to draw a concrete conclusion on how use of a prosthesis changes gaze behaviour during manipulation unless it is subdivided into its sub-actions, something that was not addressed in this work. Nevertheless, a description of the changes associated with introducing the prosthesis and with learning to use it will be provided.

In contrast to the reaching phase, changes in gaze behaviour during the manipulation phase between baseline and prosthetic sessions were not as distinct. Nevertheless, from Figure 4. 21and Figure 4. 24, one clear difference was observed between anatomical and prosthetic hand use during manipulation phase: Only during prosthetic hand use was gaze fixated at the GCA (~8% in V2). When visually inspecting the gaze sequence data, it appeared that this fixation took place in two places:

- When the carton was lifted up and later when it was released back onto the table top.
- In some subjects sudden, though short, fixation periods at the GCA while pouring, mainly in V2, were observed.

This possibly reflects the lack of the reliable proprioceptive feedback from the prosthesis regarding the hand state causing uncertainty of the hand grip around the carton.

The main role for gaze during pouring is to monitor the progress of the task including water flow and checking the water level in the glass. Such a function has been observed in an earlier study by Land (49).

Training overall showed some changes to gaze behaviour during manipulation, although less prominent than for the reaching phase. Visual carton guidance decreased with practice, and fixation at the GCA also slightly decreased reflecting better confidence in the prosthesis grip.

In summary, prosthesis use appears to affect the ability of subjects to anticipate and plan forthcoming actions particularly in the reaching phase, a fundamental quality reflected in gaze behaviour of anatomically intact individuals performing a task that consists of a series of actions (54, 227). The gaze behaviour observed in this chapter clearly highlights the difficulty associated with prosthesis use, moving from a strategy of using gaze to plan forthcoming actions to a strategy associated with ensuring the safe performance of the ongoing action. It is reasonable to suggest that this change in strategy may be associated with additional attentional load when using the prosthesis simulator.

In contrast to the kinematic characteristics, changes to gaze behaviours over practice were not statistically significant. The gaze behaviour, however, was in general more erratic with a larger number of transitions between AOIs in V2 as compared to V4. V2 required high attention which is expected to be seen in the cognitive stage of learning according to Fitts and Posner's model (222). With practice, attentional demands during reaching decreased, as mentioned above, however, did not return to normal.

Therefore, gaze data at least suggest that autonomous stage of learning definitely was not reached by the subjects. Perhaps long intensive practice of prosthetic use is required before achieving this stage. In the following chapter, the kinematic and gaze behaviours in established myoelectric prosthesis users whom have been using prosthesis on a daily basis for years will be investigated.

### 4.7. Conclusions

In this study of anatomically intact subjects learning to use a myoelectric prosthesis, it has been shown that the kinematic and time-based results showed characteristic changes from V1 to V2 and clear effects of practice from V2 to V4. The SHAP functionality scores, time to complete the manual task, temporal movement variability, and patterns of forearm movement and aperture profile showed evidence of substantial improvement (return towards values seen in V1) over the period of the study. However, the very different patterns of gaze behaviour observed at V2 showed only relatively small changes with practice (i.e. at V4).

Prosthetic use required compensatory movements to complete the task; when the prosthesis was used, an excessive shoulder abduction to pour the water was observed. It seems that subjects realised very early in V2 the need to compensate for movement constraints resulting from the lack of wrist joint motion. Notably, they could not adapt to this constraint with practice; as shoulder abduction did not decrease significantly from V2 to V4.

Introducing the prosthesis resulted in an increase in movement duration. Movement duration continuously decreased within V2 resulting in high temporal variability between trials. This variability significantly decreased as expected (222) by V4 indicating an understanding of the requirements for successful task performance. However, temporal variability remained higher than baseline. In the reaching phase, reaching with the prosthesis was always associated with abnormal erratic and slow motion instead of ballistic motion with bell-shaped velocity profile.

In agreement with earlier studies (5, 8) prosthesis use was also associated with an abnormal plateau in the grip aperture profile implying the lack of movement planning and the high reliance on vision to guide the movement (5, 8). Importantly, during reach subjects even at V4 showed considerable visual attention to hand-related areas. Gaze data further supported the lack of planning and the reliance on visual feedback even after practice.

The existing findings suggest that at best subjects have not yet reached the “autonomous” stage in Fitts and Posner’s model (222) and hence still found using a myoelectric prosthesis to be attentionally demanding. Future work is required to better understand this effect.

Changes in SHAP functionality scores across the study seemed to agree with many kinematic measures and this can be an indication of the sensitivity of SHAP to changes in motor performance.

Chapter 5 describes the results of a related experiment, but in upper limb amputees. There were two aims to the study. The first aim was to investigate the validity of using anatomically intact subjects as a framework for future investigations of new prostheses and training approaches. The second aim was to investigate relationships between amputee performance measured on well validated clinical tools and performance on the task used in this chapter.

## Chapter 5: Visuomotor behaviours during performance of a functional task in amputees who use myoelectric prostheses and their relationships with established clinical measures.

### 5.1. Introduction

In the study reported in Chapter 4, it was shown that multiple kinematic and gaze behaviours are severely disrupted in anatomically intact subjects when they first use a prosthesis to complete an ADL task. Not only did the introduction of the prosthesis cause a major drop in hand functionality score, it caused a slowing in overall speed of task performance and skewed the relative timing of events in the task. For example, peak aperture occurred later in the reaching phase. Temporal variability of arm acceleration trajectories increased by almost 7-fold in reaching and by 2-fold in manipulation. However, joint angle trajectories were largely unaffected, apart from shoulder adduction/abduction range of movement during manipulation phase, which greatly increased to compensate for reduced pronation/supination.

As well as a rapid and significant improvement in SHAP scores, a small number of kinematic measures showed significant improvement (shift towards values seen at baseline) over the period of practice; namely, task duration, temporal variability during both reaching and manipulation phase, time to peak aperture, and peak velocity. However, none of the kinematic measures returned to their baseline values by the end of practice. It is reasonable to assume that some or all of these changes may reflect skill acquisition.

Gaze behaviours were also severely disrupted on first introduction of the prosthesis. Specifically, the pattern of attention to AOIs in reaching was dramatically altered; in contrast to the behaviours seen at baseline, subjects focused for some of the reach phase on hand-related areas and notably paid considerable attention to areas of the carton related to the grasp. Subjects showed little or no evidence of behaviours in reach that could be interpreted as planning ahead. Most of the changes to both the kinematic and gaze behaviours seen on first use of the prosthesis suggested decrement in performance in comparison to the baseline; since they collectively suggested a shift from ballistic and rhythmic performance that is executed based on pre-set kinematic plan in the baseline into a slowly executed and visually monitored performance.

None of the gaze variables showed significant differences in value over the period of practice, although there was a general trend towards improvement in almost all variables. Notably, at

V4 gaze behaviour remained disrupted when compared with baseline; a high number of transitions were observed and there was little or no evidence of planning ahead and attention to the hand during reaching was still clearly evident.

Using a prosthesis simulator in anatomically intact individuals is an approach that has been used in several previous studies of both upper and lower limb prostheses (115, 136-138, 228, 229). Using a prosthesis simulator has several advantages in early stage studies over attempting to recruit amputees. First, it provides an opportunity to explore motor behaviour in a large testing sample which is often otherwise difficult to obtain due to limited numbers of upper limb amputees. Additionally, in anatomically intact individuals, it is possible to control the testing conditions; for instance, all subjects can be fitted with prosthetic sockets that have identical configurations, and equally important, with a specific hand and hence myoelectric control strategy. These aspects are extremely difficult to control for in studies involving amputees. Furthermore, investigating motor learning in new amputees is perhaps unethical due to the additional burden associated with experimental work, on top of the amputee getting used to his condition.

The study in Chapter 4 provided insight into the changes to visuomotor behaviour that occur in anatomically intact subjects following the introduction of a prosthesis and with a short period of practice. However, in order to have confidence in using such an approach to study related problems in the future, it is important to understand whether or not this approach was a valid model (i.e. whether the behaviours seen in healthy subjects using a prosthesis were reflective of behaviours seen in amputee subjects).

Finally, although the changes in measures of skill seen with practice in the study in Chapter 4 were interpreted as being reflective of skill acquisition, it was not established how these may relate to clinical evaluation tools of hand function and measures reflective of the ability of amputees to use their prosthesis in everyday life. A few studies in the past explored the relationship between kinematic measures and clinical evaluation tools (7, 115, 133, 141, 143); however, the agreement was rarely clearly established. This is likely because most of these studies reported kinematic measures for non-functional goal-directed pointing tasks (141) or constrained cyclic tasks (e.g. turning a crank) (143). For instance, in a case study of a trans-humeral amputee learning to use a new prosthesis (141), the performance was found to deteriorate with introducing a new prosthesis, then improve over training, according to standard clinical evaluation tools. However, the movement characteristics (including peak velocity, endpoint error and endpoint variability) of a planar pointing task remained relatively unchanged with introduction of the prosthesis and only movement velocity increased over practice. In another study in trans-humeral amputees by Popat et al (143) in which different prosthetic elbow control schemes were compared, although movement kinematics while turning a crank were shown to reflect the functional differences between different control schemes, the differences were not shown in time to complete ADLs; a common measure in clinical evaluation tools.

Therefore, this chapter reports on a study of visuomotor behaviours in amputee users of myoelectric prostheses. As a first study in amputees, it aimed to:

1. Explore visuomotor behaviours of experienced prosthesis users;

2. Describe visuomotor behaviours associated with both the anatomical and prosthetic arm performance of an ADL manual task in unilateral amputees. This is to explore the similarity between the amputees' performance with the anatomical and prosthetic arms and performance of anatomically intact subjects seen at V1 and V4 respectively (i.e. after a period of practice) in the study reported in Chapter 4. The outcomes would address the question of whether the use of anatomically intact subjects to study upper limb prosthesis control was a valid approach;

3. Investigate the extent of the agreement between the proposed measures of skill and validated clinical measures of hand functionality, upper limb functional status and functional restriction.

## 5.2. Methods

### *5.2.1. Subjects*

The study protocol was approved by the University of Salford Ethics Committee (Ref # REP11/028) and Northwest 10 NHS Research Ethics Committee (Ref # 11/NW/0060).

Amputee subjects were recruited from the Manchester Disablement Services Centre (DSC), University Hospital of South Manchester (UHSM). The recruitment procedure and overview of the protocol is shown in Figure 5. 1.

The inclusion criteria for this study were:

- Unilateral, trans-radial amputee;
- Fitted with myoelectric prosthesis whose hand is controlled by two-site, two function control scheme;
- Able to use their prosthesis to reach for a carton and pour from it into a glass (with or without visual correction from glasses or contact lenses);
- No history of epileptic seizures triggered by light flashes or patterns;
- Able to give oral and written consent;
- Aged over 18.

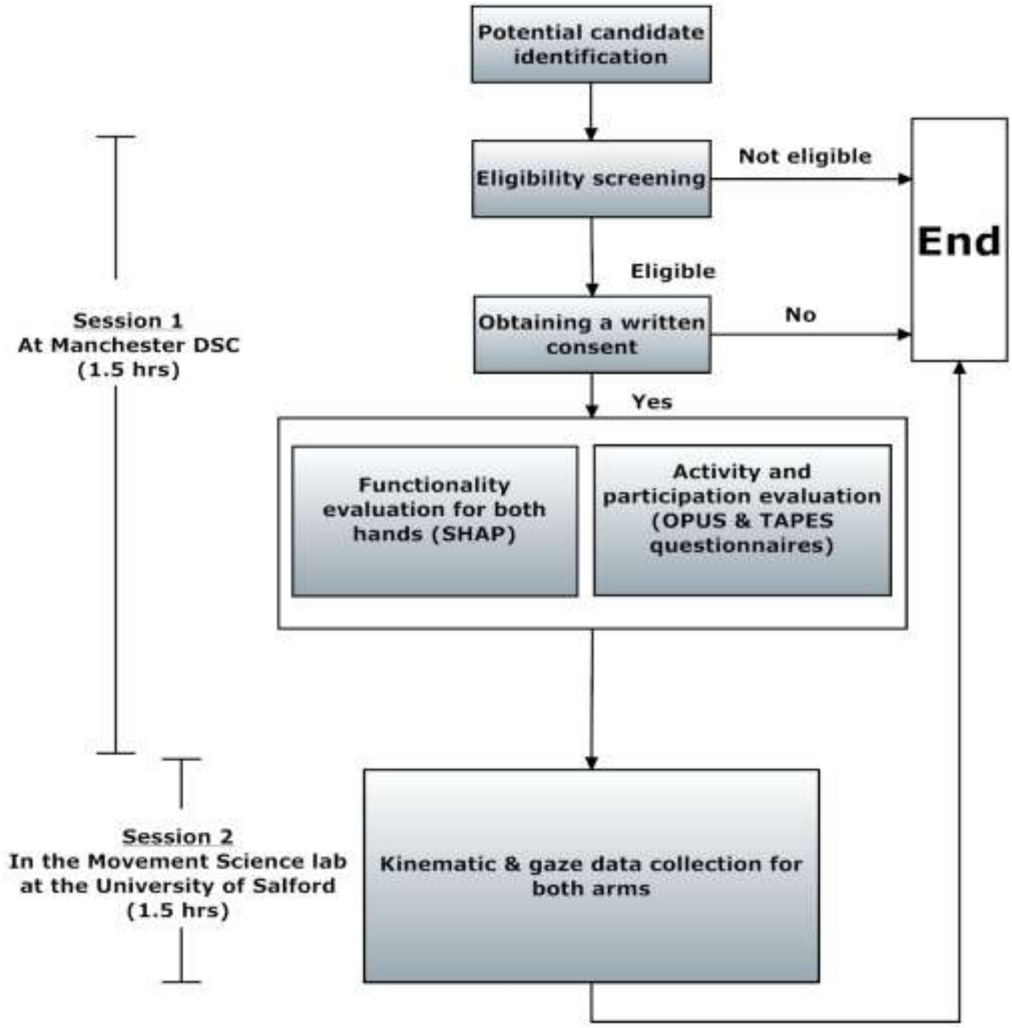



Figure 5. 1: Recruitment and experimental procedure.

Twelve potential subjects who are established trans-radial myoelectric prosthesis users were approached by their Occupational Therapist (OT) to take part in this study. Of those, six subjects verbally agreed to take part in the study. However, one subject reported a mechanical problem with his prosthetic hand and hence could not participate. Another subject could not attend the second testing session, and therefore his data are not reported here. Four subjects, following informed consent, completed the protocol. Table 5. 1 summarizes the subjects' details and describes technical features of their prosthesis.

| | **Subject 1** | **Subject 2** | **Subject 3** | **Subject 4** |
|---|---|---|---|---|
| Gender | Male | Male | Female | Male |
| Age | 55 | 51 | 35 | 56 |
| Height (cm) | 170 | 175 | 170 | 175 |
| Limb dominancy | Right | Right | Left | Right |
| Amputated side | Right | Right | Right | Right |
| Time since amputation (years, months) | 4, 2 | 29, 2 | 35, 0 | 34,0[***] |
| Amputation | Cancer | Traumatic | Congenital | Traumatic |
| Time since first myoelectric prosthesis (years, months) | 2, 2 | 25, 0 | 32, 0 | 22, 0 |
| Residual limb length (cm) | 17.5 | 9 | 9.5 | 16 |
| Hand | Otto Bock SensorHand Speed | Otto Bock SensorHand Speed | Otto Bock SensorHand Speed | RSL Steeper MultiControl Plus |
| Maximum opening /closing speed (from (115)) | 236.4 °/s | 236.4 °/s | 236.4 °/s | 69 °/s |
| Hand size (in) | 7 ¾ | 8 ¼ | 7 ¼ | 8 ¼ |
| Weight | 464 g | 464 g | 464 g | 214 g |
| Pressure sensors for slippage detection | Yes | Yes | Yes | No |
| Powered wrist rotator | No | Yes | Yes | No |

Table 5. 1: Subject details and technical features of their prosthesis.

[***] The trauma was in 1970 and resulted in loss of fingers only. Seven years later a trans-radial amputation was carried out.

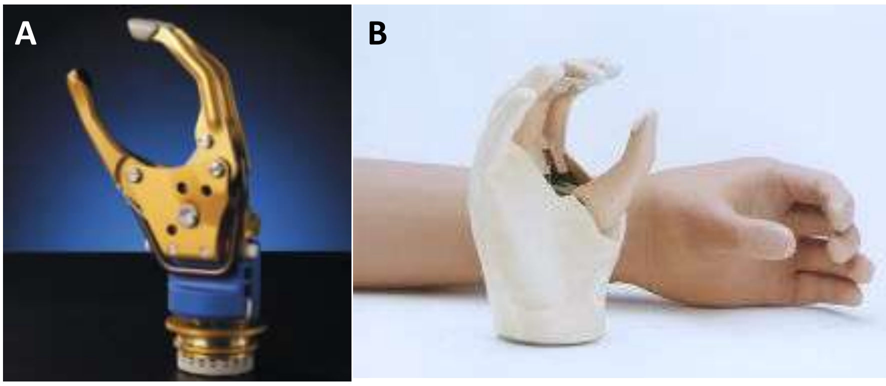



Figure 5. 2: (A) Otto bock SensorHand Speed® (from (230)) and (B).RSL Steeper MultiControl™ Plus hand (from (231)).

Two prosthetic hands were used by the subjects in this study; Otto Bock SensorHand Speed® (by Subject 1, Subject 2 and Subject 3) and the relatively old design RSL Steeper MultiControl™ Plus (by Subject 4). The two hands are illustrated in Figure 5. 2. In this study all subjects used two-site two-state control strategy which provides (as described in Chapter 2) control over the hand state with a fixed speed. The finger tips of SensorHand Speed are equipped with pressure sensors to control the grip force and prevent slippage [†††]. RSL Steeper MultiControl™ Plus has soft finger tips which allow for accommodating objects with irregular shapes, but does not automatically control grip force to prevent slippage. The most notable other difference between the hands is the speed of operation. RSL Steeper MultiControl™ Plus operates at approximately 1/3 of the speed of Otto Bock SensorHand Speed®.

### *5.2.2. Testing procedure*

The study was completed in two sessions. Session 1 was conducted by the Occupational Therapist (OT) at Manchester Disablement Services Centre (DSC) and lasted approximately 1.5 hours. Session 2 was conducted by Mohammad Sobuh at the University of Salford's movement science laboratory and lasted approximately 1.5 hours.

#### *5.2.2.1. Session 1*

First, potential subjects were screened for eligibility based on the inclusion criteria described above. Following signing of a consent form subjects completed two standardised questionnaires, the Orthotics and Prosthetics User Survey (OPUS) with its Upper Extremity Functional Status (UEFS) module (105, 110), and Trinity Amputation and Prosthesis

[†††] http://www.ottobock.com/cps/rde/xchg/ob_com_en/hs.xsl/3652.html (24/01/2012).

Experience Scales (TAPES) (109, 111). Finally, subjects completed the SHAP clinical test of hand functionality (25), first using the anatomical arm and then using their prosthesis. In the context of this chapter, the TAPES, OPUS and SHAP will be collectively referred to as clinical evaluation tools of upper limb prostheses.

*The Orthotics and Prosthetics User Survey (OPUS) (105, 110)*

OPUS is a questionnaire comprising three modules focusing on functional status, health-related quality of life and subject's satisfaction respectively. OPUS is directed to upper limb and lower limb prosthesis users, as well as to users of orthoses. In this study, only the Upper Extremity Functional Status (UEFS) module is reported, which has recently been revised and validated (110). In the UEFS, subjects are instructed to score both the difficulty they find in performing each of 19 ADLs on a 4 point ordinal rating scale (0 = cannot perform activity; 1 = difficult; 2 = easy; 3 = very easy). In addition, subjects are asked to state whether or not they perform each of the tasks using their prosthesis. The UEFS of OPUS questionnaire is listed in Appendix J.

*Trinity Amputation and Prosthesis Experience Scales (TAPES) (109, 111)*

TAPES in its original form, is a 54-item self-administrated questionnaire divided into three modules focusing on:

- The adaptation of the amputee to their amputation and prosthesis use (psychosocial adjustment module);
- The level of activity restrictions that the amputee experiences in everyday life (activity restriction module);
- Satisfaction with the prosthesis and provided services (satisfaction module).

Each of these modules comprises one or more subscales, each of which includes a number of statements/questions. The responses to statements/questions are scored on ordinal rating scales. Additionally, the TAPES assesses phantom and residual limb pain and other medical problems. TAPES was originally developed for lower limb amputees (111), and subsequently the internal reliability of subscales of the TAPES for use with acquired upper limb amputees was established (109).

The original format of TAPES is available at http://www.psychoprosthetics.ie/tapes-r.html. For the purpose of this study, the TAPES was modified to meet the requirement of upper limb evaluation as instructed in the guide to TAPES (see (232)).

*Southampton Hand Assessment Procedure (SHAP) (25)*

As described in Chapter 4, SHAP is an objective observational test to measure hand function (whether prosthetic or anatomical). The SHAP comprises completion of 26 timed tasks; 12 abstract object tasks and 14 ADL tasks. Scoring is based on the time taken to complete each task. When performing SHAP subjects are instructed to use their prosthetic hand as long as the task can be achieved unilaterally, and as a main manipulator when the task is bimanual. Subjects also are encouraged to use the natural gripping patterns (power grip, lateral grip, tip grip, span or spherical grip, tripod grip and extension grip) while grasping the objects. SHAP procedure is currently available at http://www.shap.ecs.soton.ac.uk/about-pubs.php.

All 4 subjects were asked to perform the SHAP as instructed, using all prosthetic technical features that they usually use in everyday life (i.e. subjects who reported normally using an electrically powered wrist unit to perform the tasks, were encouraged to use the wrist unit when performing SHAP).

##### *5.2.2.2. Session 2*

Session 2 involved subjects performing the same functional task, as described in Chapter 4 namely, reaching for a carton, pouring water from the carton into a glass and returning the carton to its starting place. Upper limb kinematics and gaze behaviour were recorded during the performance of the task.

*Movement kinematics and gaze behaviours*

In order to gather arms and torso motions and gaze behaviour while completing the ADL manual task in session 2, Vicon 612® motion capture system (Vicon Motion Systems, Los Angles, USA) and iView X™ HED 2 (SenseMotoric Instruments GmbH, Tellow, Germany) Eye Tracking system were used respectively. Both Vicon 612® and iView X™ HED 2 systems are described in detail in Section 4.2.1.2 in Chapter 4 and Section 3.2.6 in Chapter 3 respectively.  However, marker data configurations were slightly different and hence a Table and a Figure describing the marker arrangements are provided below (Table 5. 2 and Figure 5. 3). In summary, markers were attached to the trunk, both upper limbs and carton. Processing of both the kinematic and gaze data were exactly as described in Chapters 4, Section 4.3.2.1 and 4.3.2.2 respectively.

| ***Anatomical markers*** | ***Marker label*** |
|---|---|
| Right and left most caudal-lateral point on the ulnar styloid | R-U-Sty, L-U-Sty |
| Right and left most caudal-lateral point on the radial styloid | R-R-Sty, L-R-Sty |
| Right and left most caudal point on medial humeral epicondyle | R-M-Epi, L-M-Epi |
| Right and left most caudal point on lateral humeral epicondyle | R-L-Epi, L-L-Epi |
| Right and left most dorsal point on the acromioclavicular joint | R-AC, L-AC |
| Spinal process of the $7^{th}$ cervical vertebra | C7 |
| Spinal process of the $8^{th}$ thoracic vertebra | T8 |
| Deepest point of Incisura Jugularis | IJ |
| Xiphoid process: Most caudal point on the sternum | XP |
| ***Technical markers*** | |
| Torso cluster: Middle of the sternum | C11-C14 |
| Left upper arm cluster: Middle of the lateral boarder of the left upper arm | C21-C24 |
| Left forearm cluster: Middle of the lateral boarder of the left forearm | C31-C34 |
| Carton: Uppermost quarter of the carton | C41-C44 |
| Right upper arm cluster: Middle of the lateral boarder of the right upper arm | C51-C54 |
| Prosthetic (right) forearm cluster: Middle of the lateral boarder of the prosthetic forearm | C61-C64 |
| Middle of tip of the left thumb | L-F1 |
| Middle of tip of the left index | L-F2 |
| Middle of tip of the prosthetic thumb | R-F1 |
| Middle of tip of the prosthetic index | R-F2 |

Table 5. 2: Reflective marker placement. Note: When the prosthesis was used, R-U-Sty and R-R-Sty markers were placed on the wrist unit and R-M-Epi and R-L-Epi markers on the socket over the medial and lateral humeral epicondyles respectively.

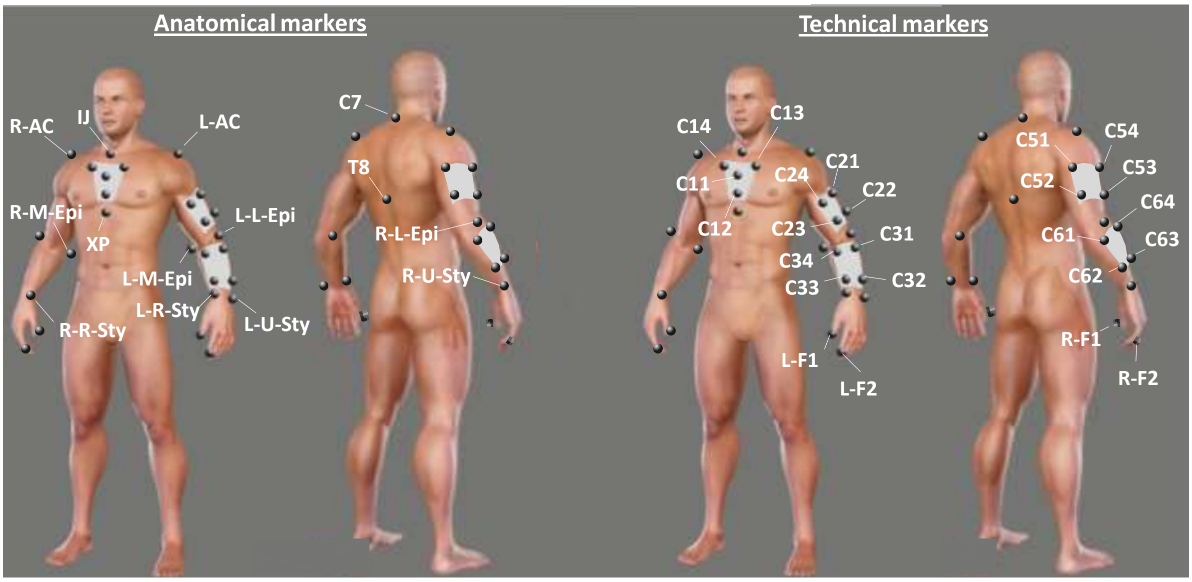



Figure 5. 3: Anatomical and technical marker setup for the body's segments. Note: Due to difficulties in illustrating all markers in one view, two views are shown for both the anatomical marker set and technical marker set (viewed from front and rear). Further, in each illustration, all visible markers are shown, but only the relevant subset is labelled. The technical markers C41-C44 are attached to the carton and they are shown in Figure 4.2 in Chapter 4.

*ADL manual task performance*

In session 2, subjects were invited to complete the manual task described in Chapter 4 (pouring water from a carton) first using their anatomically intact arm and then using their prosthesis. Task completion was exactly as described in Chapter 4. Briefly, each subject was seated with his/her back straight and supported by the back of the chair, upper arms in a neutral position with both hands resting comfortably on the table, and hence elbows flexed at about $90^0$. The carton was placed on the same side of the hand to be used at a reachable distance from the subject so he/she does not need to lean forward to complete the task. The glass was placed to the side of the carton in front of the contralateral hand. The locations of the hands when rested on the table, carton and glass were marked on a paper sheet covering the table top and remained unchanged throughout the experiment for each subject.

The task required subjects to reach out and grasp a carton, pour 200 ml water into a glass, and then return the carton to its original position on the table. At the end of the task, subjects were instructed to place their hands back on the table at the marked hand start positions.

Prior to starting the task, subjects were instructed to gaze at a marked point (termed the gaze reference point (GRP) which was placed in the middle of the table 10 cm from the distal end of the table. This point served as a visual start and end point for all subjects throughout the test. During task completion, subjects were free to move their eyes as they wish. Furthermore, no constraint on head movement was applied during the task performance. At the end of task completion, subjects were instructed to return their gaze to the GRP.

Subjects were encouraged to perform the task as accurately as possible and to avoid water spillage. Subjects were also asked about the way they perform this task in everyday life. None of the subject reported performing this task using their prosthesis, probably because it is a unilateral task that could be performed more conveniently using the anatomically intact arm. Therefore, they were instructed to mimic the performance of the anatomically intact arm which was always tested first.

Subject 2 and 3 both of whose prostheses are fitted with a myoelectrically controlled wrist unit were able to perform the task either with, or without using the wrist unit. Subject 2 was asked to perform the task with the wrist unit turned off. An amendment to the ethical approval to address this problem was submitted and approved (Ref # 11/NW/0060, amendment 1, 20/07/2011) and the subject invited back. Unfortunately, the subject did not respond to the invitation. Subject 3 performed the task with the wrist unit active.

Each subject completed the task 15 times with the anatomically intact arm and 15 times with the prosthetic arm. The exception to this was subject 3 who was asked to complete the task 25 times with each arm in order to gather sufficient usable data sets. The first 10 trials with adequate marker visibility and gaze data of sufficient quality for analysis were then considered in the analysis.

## 5.3. Data analysis

### *5.3.1. Clinical evaluation tools*

#### *5.3.1.1. The UEFS of OPUS*

Analysis of the Upper Extremity Functional Status module was based on recommendations in (110). Scoring was completed using a template in which the responses to each item are scaled on an equal interval measure (logit measure) ranges between -6 and 8. The distribution of and the distance between the responses of the items in the interval measure vary depending on the difficulty of the item as seen in Figure 5. 4. The threshold between adjacent scoring categories is marked by “:”. Scoring involves circling the responses of each item, then estimating a vertical “regression” line that best fits all scores. The point where the regression line intersects the horizontal axis is the estimated measure in logit units for that person. Logit score of zero (in Figure 5. 4), represents average functional status, negative values indicate lower functional status, and positive values indicate higher functional status.

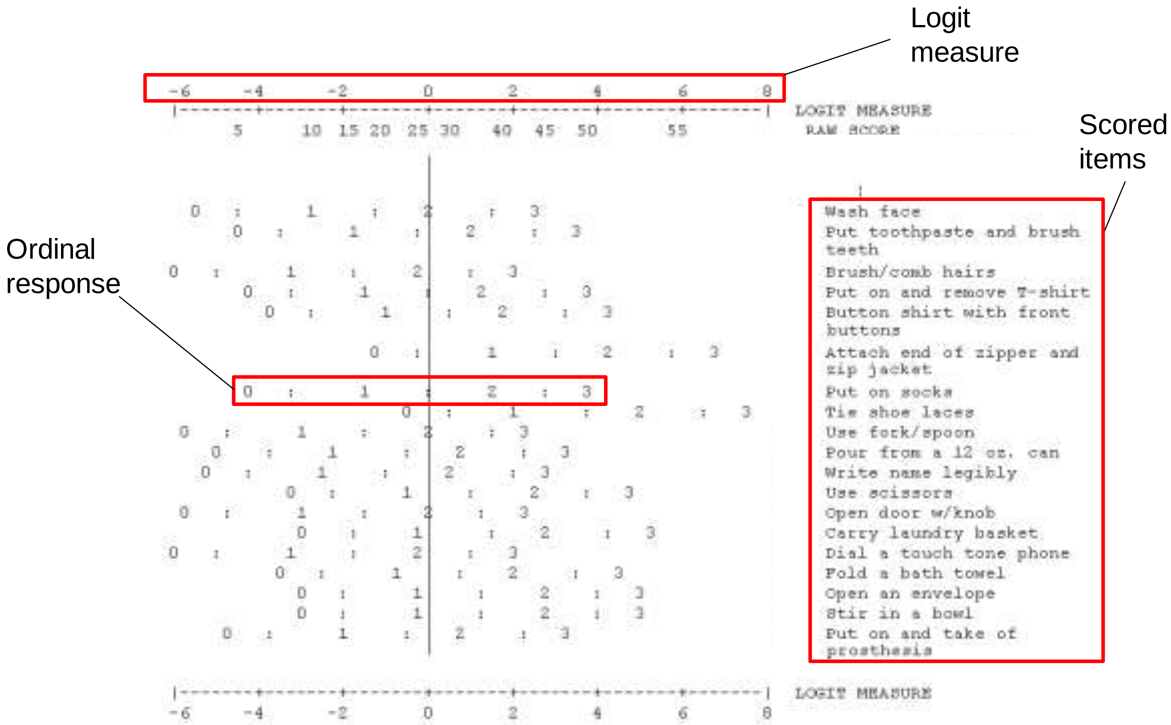



Figure 5. 4: Template for scoring the UEFS module in OPUS, (from (110)). In this template, the right column lists the ADLs scored in this module (referred to as the scored items). The ordinal responses for each ADL are listed to the left of the corresponding ADL. The ordinal responses are scaled on logit measure in which the distribution of and the distance between the ordinal responses of the items vary depending on the difficulty of the item. The mark “:” represents a threshold between adjacent scoring responses for a particular ADL. Scoring involves circling the responses of each item, then estimating a vertical “regression” line that best fits all scores. The point where the regression line intersects the horizontal axis is the estimated measure in logit units for that person.

#### *5.3.1.2. TAPES*

In TAPES, the score for each subscale is the sum of the scores given to each item. The psychosocial adjustment subscale is scored out of 70, where higher scores indicate better adaptation to amputation and prosthesis use. The activity restriction subscale is scored out of

24, the higher the score the greater the degree of activity restriction. The satisfaction module is scored out of 50; a higher score indicates a higher level of satisfaction.

#### *5.3.1.3. SHAP scores*

Based on the time taken to complete each of the 26 SHAP tasks, a functionality profile of each prehensile pattern is calculated. An overall functionality score is then obtained using the web-based software produced by the developers of the evaluation tool (http://www.shap.ecs.soton.ac.uk/entry.php) (25). SHAP scoring was discussed in 4.3.1 in Chapter 4.

### ***5.3.2. Kinematic and gaze data***

The analysis of kinematic and gaze data was identical to that described in Chapter 4. Briefly, from the kinematic data, 3D shoulder joint angles and elbow angle in the sagittal plane were calculated from relevant marker data throughout the task using Visual 3D software. Also using Visual 3D, the 3D position of the wrist joint relative to the global coordinate frame was calculated and then used to calculate the linear velocity of the wrist joint centre.

Additionally, forearm acceleration in the local coordinate system, and hand aperture and carton 3D global position were calculated using SMAS (213), a MatLab based toolkit. Using the same criteria as in Chapter 4 (see Chapter 4, Section 4.3.2.1), the task was segmented into reaching and manipulation phase. For the reaching phase, shoulder and elbow range of motion (ROM), temporal and magnitude variability in the forearm acceleration, hand aperture and wrist velocity were calculated. In addition, the time to complete the phase was calculated. For the manipulation phase, shoulder and elbow ROM, temporal and magnitude variability in the forearm acceleration were calculated, in addition to the time to complete the phase.

Gaze data were coded using the previously established coding scheme for this particular task (216). The development, validation and final version of the coding scheme are described in Chapter 3. As a reminder, 15 categories were defined (see Table 4. 3 in Chapter 4); 14 of which correspond to an "area of interest" (AOI) in the scene ahead (see Figure 4. 9 in Chapter 4), with the $15^{th}$ corresponding to saccades, blinks and missing data.

From the gaze data, gaze sequence between AOIs during reaching and during manipulation phase was shown separately. To represent the sequence of gaze behaviour, gaze data were first normalised by dividing the fixation duration at each AOI by phase duration. Then gaze sequence was presented in stacked bars in which each coloured portion of the bar corresponds to the percentage fixation at a single AOI.

Number of gaze transitions in each phase was calculated for each phase in each trial. Then the average number of transitions per phase for each arm was calculated. To consider a transition, the gaze should move from one AOI to another, thus if gaze stayed in the same AOI after a saccade, this was not considered as a transition.

Finally, the average normalised gaze duration across all 10 trials for each AOI was calculated for each arm. Gaze duration is defined as the sum of all fixations made on an AOI (194) in a given phase of a trial. The gaze duration was normalised by the duration of the phase. For each subject and arm data, the normalised gaze durations were averaged over the 10 trials. To compare between prosthetic and anatomical arm performance, the average gaze duration for all 4 subjects was calculated for each arm.

#### *5.3.3. The correlation between clinical evaluation tools and measures of skill*

To explore the correlation between clinical evaluation tools and measures of skill, the subjects were ranked in descending order based on their clinical results and measures of skill. Then the ranking obtained from each measure was plotted against the ranking obtained from each clinical tool. For OPUS, only the Upper Extremity Functional Status (UEFS) module was considered in ranking the subjects, and for TAPES both Psychosocial Adjustment and Activity Restriction modules were used due to their relevance.

### 5.4. Results

The results are presented subject by subject, unless otherwise stated. Where relevant, the black and gray bars in each graph represent the mean values when amputee subjects used their anatomical and prosthetic hand respectively. To aid interpretation of the results of this study in the context of the findings from Chapter 4, the relevant values obtained at V1 (baseline) and V4 (after completion of the training sessions) in Chapter 4 are also plotted. Specifically, to illustrate whether the mean values of kinematic and gaze variables for each subject lie within the ranges predicted from the study in Chapter 4, 95% confidence intervals (CIs) of the means obtained at V1 (baseline, subjects using anatomical hand) and V4 (final session, subjects using prosthesis) in Chapter 4 are presented in error bars. For ease of visualisation, in the following graphs (where appropriate) CI from V1 are aligned with the mean values obtained in the amputee subjects measured when using their anatomical hand (red error bars); CI from V4 are aligned with the mean values obtained in the amputee subjects when using their prosthesis (blue error bars ).

As it is difficult to illustrate the within session variability of the data collected in Chapter 5 on the same graph as the CI from Chapter 4, and for completeness, following each graph a table that lists the values of mean and ±1 SD of the plotted measures in the graph for the four amputees using their anatomical and prosthetic arm is shown.

### *5.4.1. Upper limb prosthesis clinical evaluation tools*

#### *5.4.1.1. OPUS*

The results from the response to the UEFS of OPUS questionnaire are presented in Table 5. 3.

| | **Subject 1** | **Subject 2** | **Subject 3** | **Subject 4** |
|---|---|---|---|---|
| **UEFS module (-6-8)** | 3.2 | 3.8 | 3.8 | 3.6 |

Table 5. 3: Results of the UEFS of OPUS.

Table 5. 4 lists the activities included in the UEFS of OPUS. In addition, the table indicates when the activity is achievable by the prosthesis for every subject. Finally, a summary for the total number of activities that are achievable for each subject is shown in the last row of the table.

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 |
|---|---|---|---|---|
| 1. Wash face | × | × | × | × |
| 2. Put toothpaste on brush and brush teeth | √ | × | √ | √ |
| 3. Brush/comb hair | × | × | × | × |
| 4. Put on and remove T-shirt | √ | × | √ | √ |
| 5. Button shirt with front buttons | √ | √ | × | × |
| 6. Attach end of zipper and zip jacket | √ | √ | √ | √ |
| 7. Put on socks | √ | √ | × | √ |
| 8. Tie shoe laces | √ | √ | √ | √ |
| 9. Use fork or spoon | √ | × | √ | × |
| 10. Pour from 12 oz can (340 ml) | × | √ | × | √ |
| 11. Write name legibly | × | √ | × | √ |
| 12. Use scissors | × | × | × | × |
| 13. Open door with knob | × | √ | × | × |
| 14. Carry laundry basket | √ | √ | √ | √ |
| 15. Dial a touch tone phone | × | √ | × | √ |
| 16. Fold a bath towel | √ | √ | √ | √ |
| 17. Open an envelope | √ | √ | √ | √ |
| 18. Stir a bowl | √ | √ | √ | √ |
| 19. Put on and take off prosthesis | × | × | × | √ |
| **Total number of achievable ADLs** | **11** | **12** | **9** | **13** |

Table 5. 4: A list with the activities included in the UEFS of OPUS; "√" means that the activity is achievable by using the prosthetic arm and "×" means that the activity is not achievable.

### *5.4.1.2. TAPES*

The results from the responses to the TAPES questionnaire are presented in Table 5. 5. Each module and its underlying subscales are scored separately. The range for each module is given in brackets. For psychosocial adjustment module and satisfaction module, higher scores indicate better adjustment and satisfaction respectively; whereas in the activity restriction module, a higher score indicates higher restriction.

| | **Subject 1** | **Subject 2** | **Subject 3** | **Subject 4** |
|---|---|---|---|---|
| General adjustment (0-15) | 15 | 15 | 15 | 15 |
| Social adjustment (0-20) | 20 | 20 | 20 | 20 |
| Adjustment to limitation (0-25) | 21 | 25 | 25 | 25 |
| Optimal adjustment (0-10) | 10 | 10 | 10 | 9 |
| **Psychosocial adjustment module (0-70)** | **66** | **70** | **70** | **69** |
| Athletic activity restriction (0-6) | 2 | 0 | 0 | 2 |
| Social restriction (0-4) | 0 | 0 | 0 | 0 |
| Mobility restriction (0-10) | 0 | 0 | 0 | 0 |
| Occupational restriction (0-4) | 1 | 0 | 0 | 0 |
| **Activity restriction module (0-24)** | **3** | **0** | **0** | **2** |
| **Satisfaction with prosthesis module (0-50)** | **46** | **50** | **49** | **48** |

Table 5. 5: TAPES results.

In addition, subjects who completed TAPES were asked to state how many hours/day they wore their prosthesis and whether or not they experienced phantom limb pain. Subject 1 reported wearing his prosthesis for 14 hours/day, subject 2 18 hours/day, subject 3 15 hours/day and subject 4, 16 hours/day. None reported phantom limb pain.

### *5.4.1.3. SHAP score*

Figure 5. 5 shows the SHAP functionality index in session 1 for each subject using their anatomical and prosthetic arm. In SHAP, higher functionality corresponds to higher functionality index.

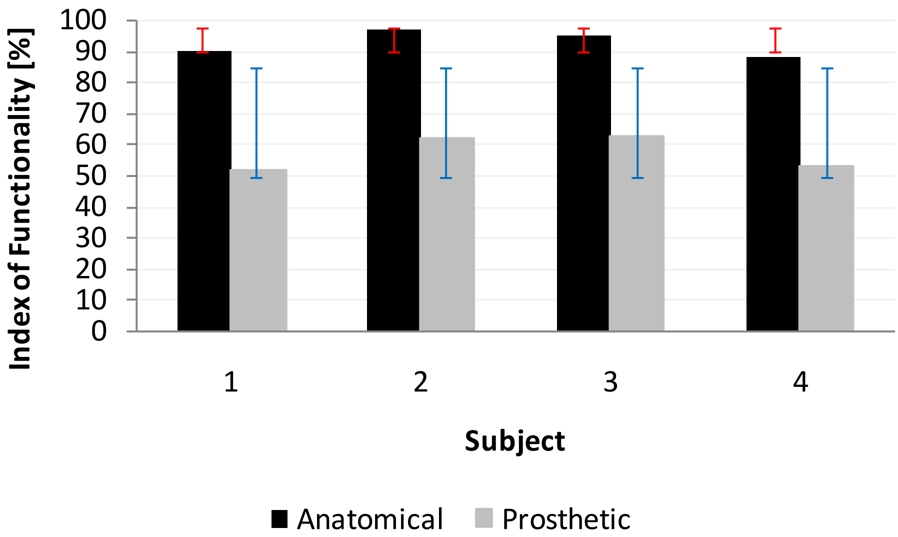



Figure 5. 5: The SHAP functionality indices measured during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at SHAP1 (baseline – shown in red) and SHAP5 (final SHAP with prosthesis– shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

### *5.4.2. Kinematic data*

#### *5.4.2.1. ADL completion duration*

Mean task, reaching phase and manipulation phase duration in session 2 for all subjects are plotted in Figure 5. 6, together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes. The mean values (and SD) for task, reaching and manipulation phase duration are shown in Table 5. 6. All subjects completed the task, reaching phase and manipulation phase faster using the anatomical arm compared to the prosthetic arm.

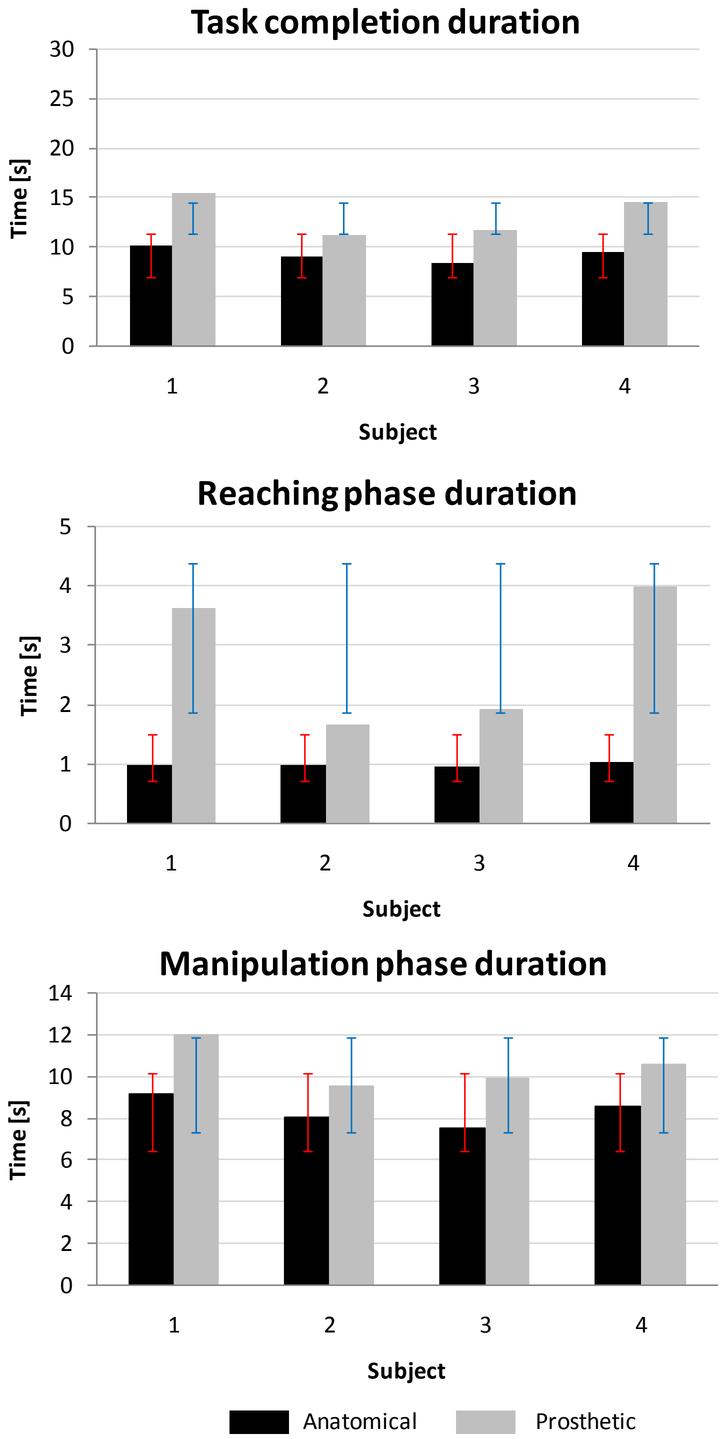



Figure 5. 6: Mean task, reaching phase, manipulation phase, completion duration, and measured during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | Subject 1 | | Subject 2 | | Subject 3 | | Subject 4 | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Task duration** | 10.1 (1.1) | 15.6 (1.7) | 9.0 (0.5) | 11.2 (0.6) | 8.5 (0.6) | 11.8 (0.8) | 9.6 (0.9) | 14.6 (1.4) |
| **Reaching phase duration** | 1.0 (0.0) | 3.6 (0.8) | 1.0 (0.1) | 1.7 (0.2) | 1.0 (0.1) | 1.9 (0.1) | 1.0 (0.1) | 4.0 (0.4) |
| **Manipulation phase duration** | 9.2 (1.0) | 12.0 (1.5) | 8.0 (0.5) | 9.6 (0.5) | 7.5 (0.5) | 9.9 (0.9) | 8.6 (0.9) | 10.6 (1.3) |

Table 5. 6: Mean task, reaching phase and manipulation phase duration (in seconds) measured when subjects used the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

Figure 5. 7 illustrates trial by trial reaching and manipulation duration of the anatomical and prosthetic arm for all subjects.

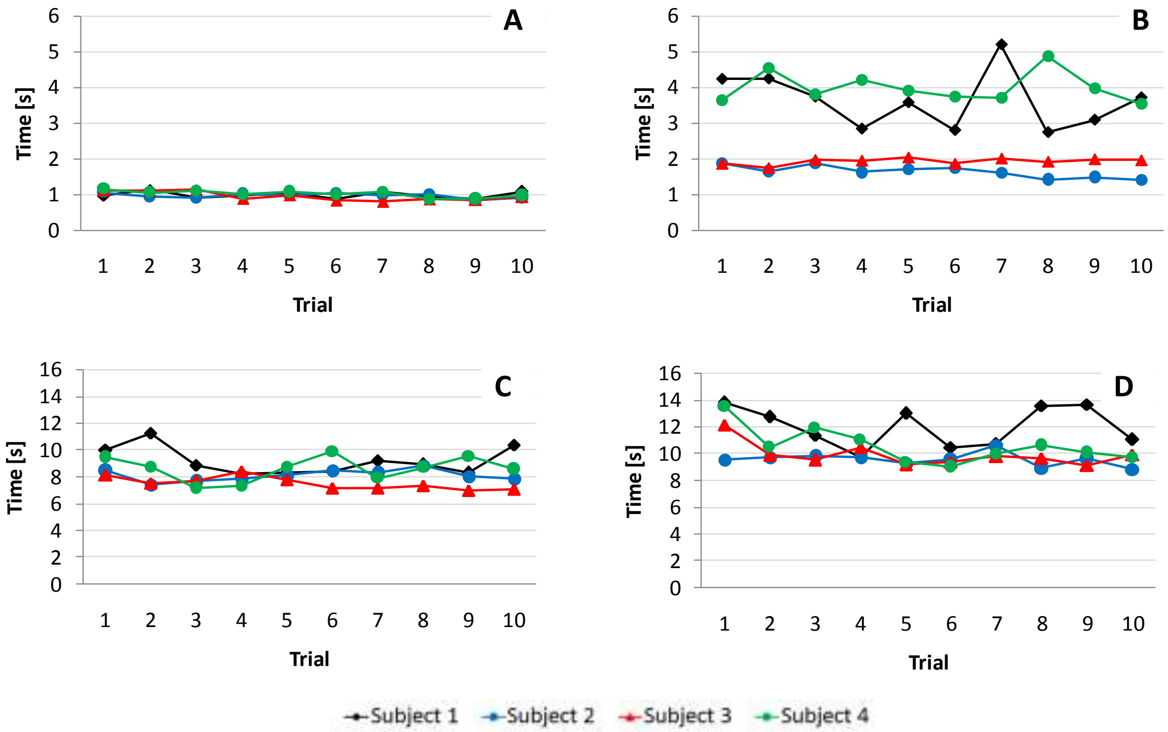



Figure 5. 7: Reaching and manipulation duration as a function of trial: (A) and (B) represent reaching duration using the anatomical and prosthetic arm respectively, (C) and (D) represent manipulation duration using the anatomical and prosthetic arm respectively. Note: Group mean of task completion duration (CIs) in seconds at V1= 9.3 (2.2), V4= 12.6 (1.6); of reaching duration at V1= 1.1 (0.4), V4 = 3.1 (1.2); and of manipulation duration V1= 8.2 (1.9), V4 = 9.5 (2.3)).

### 5.4.2.2. *Joint angles and ROMs*

The mean joint angle trajectories for all 4 subjects while using the anatomical arm and prosthetic arm for the reaching and manipulation phases are illustrated in Figure 5. 8 and Figure 5. 9 respectively. The ROMs of the shoulder joint in all planes and the elbow joint in the sagittal plane together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes are shown in Figure 5. 10 for the reaching phase, and in Figure 5. 11 for the manipulation phase . The mean (and SD) of the range of motion for each joint angle for all 4 subjects are also listed in Table 5. 7 (reach) and Table 5. 8 (manipulation) respectively.

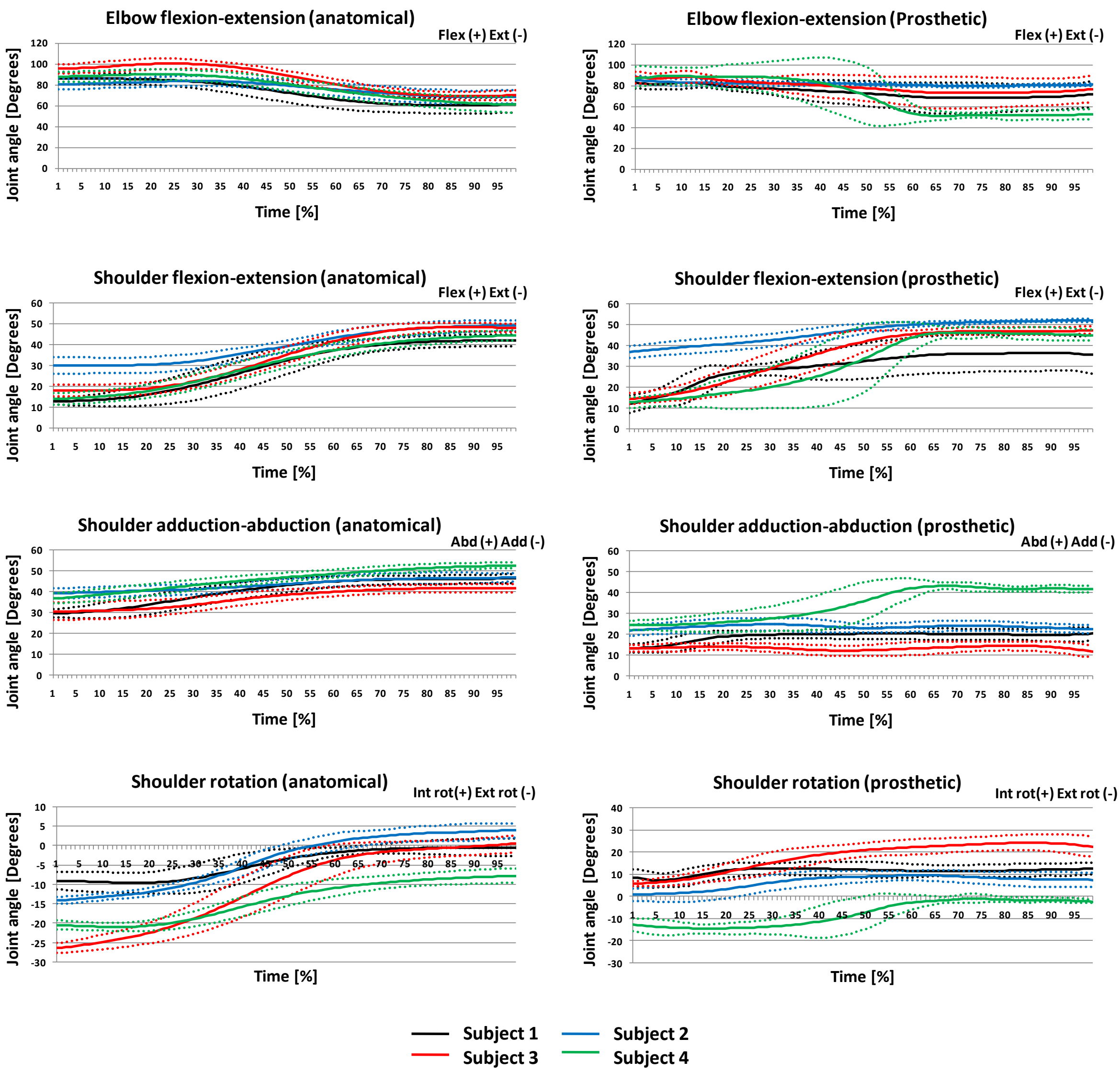



Figure 5. 8: Shoulder and elbow joint trajectories during reaching phase. Time was normalised for illustration purpose. Thin dotted lines are upper and lower confidence intervals of joint trajectories.

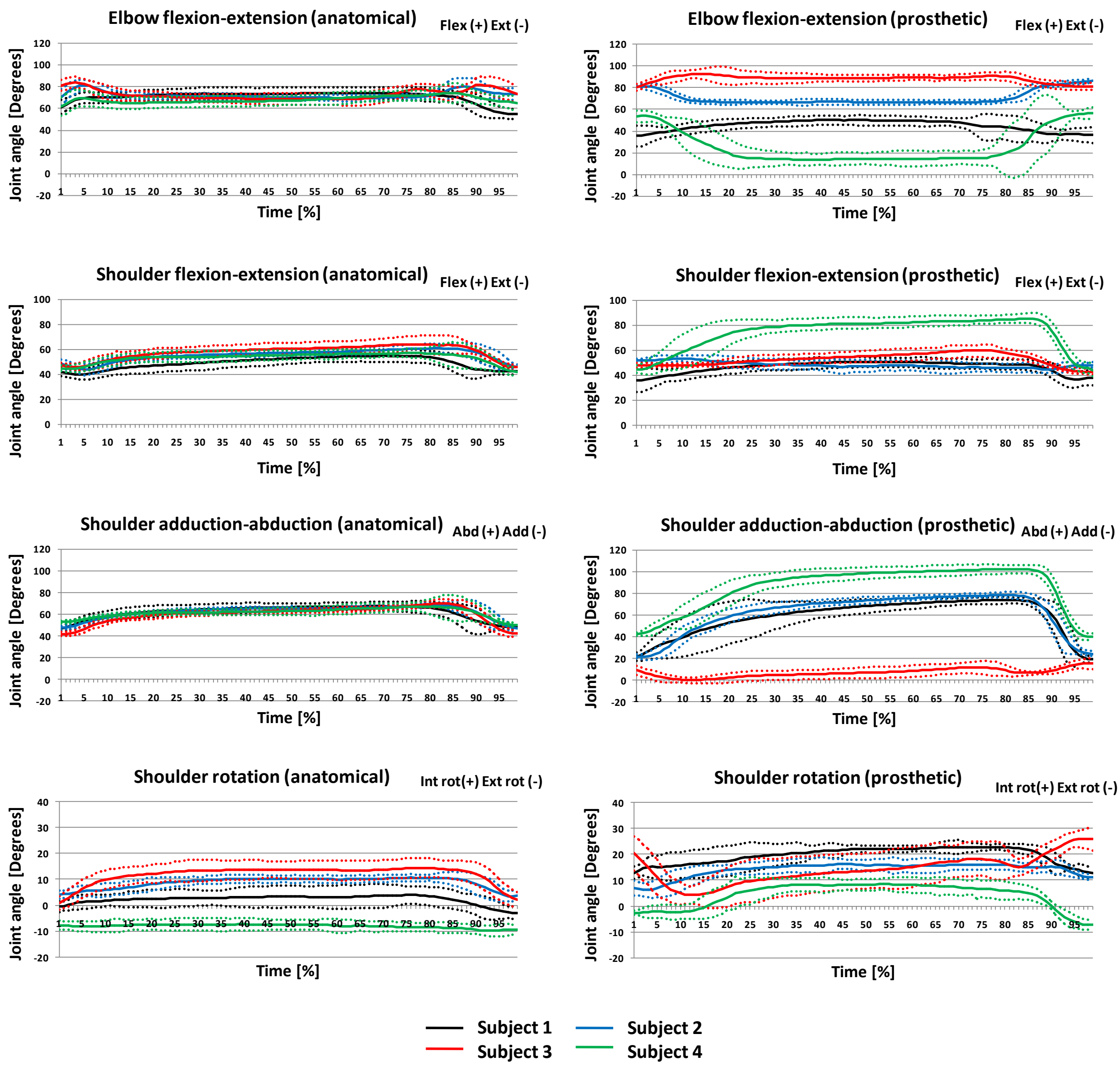



Figure 5. 9: Shoulder and elbow joint trajectories during manipulation phase. Time was normalised for illustration purpose. Thin dotted lines are upper and lower confidence intervals of joint trajectories.

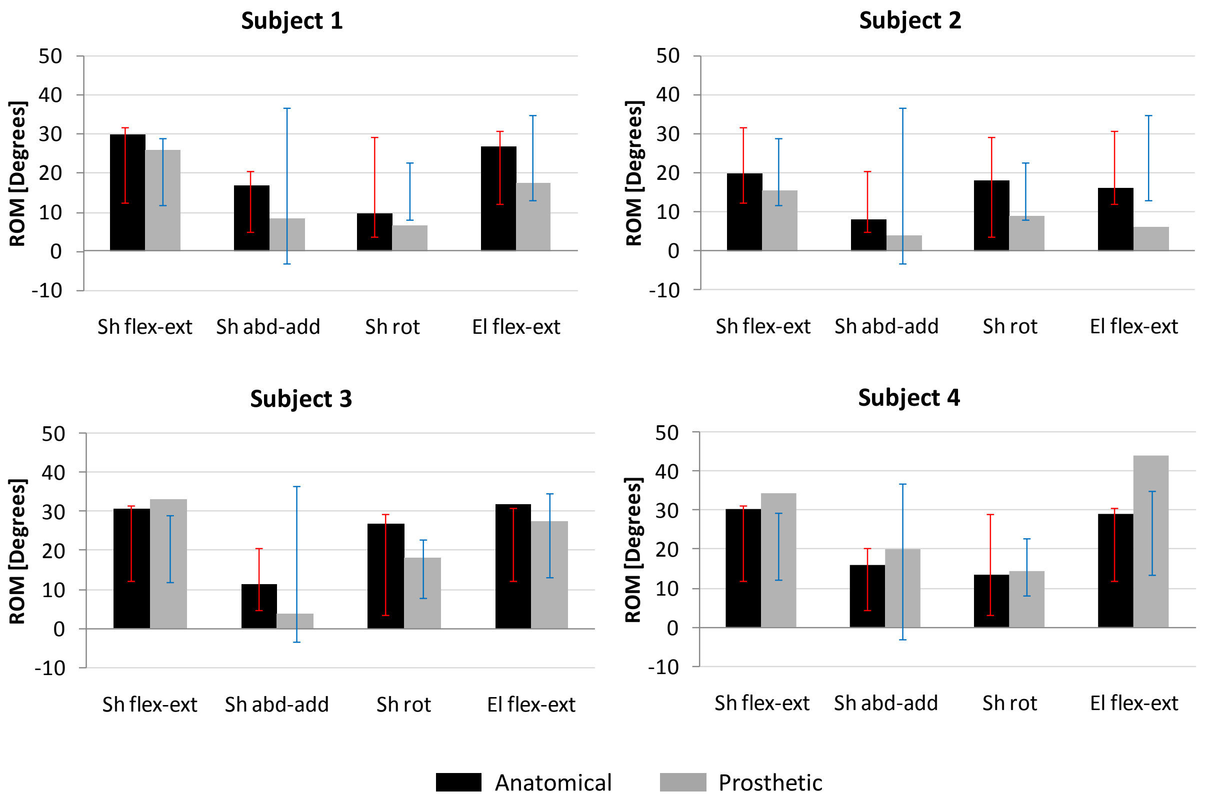



Figure 5. 10: Shoulder and elbow ROMs in reaching phase during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | **Subject 1** | | **Subject 2** | | **Subject 3** | | **Subject 4** | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Shoulder flex-ext ROM** | 29.7 (2.1) | 25.7 (5.7) | 19.8 (2.1) | 15.6 (1.7) | 30.6 (1.8) | 33.1 (1.7) | 30.5 (1.3) | 34.4 (1.6) |
| **Shoulder abd-add ROM** | 16.8 (1.2) | 8.3 (1.5) | 8.1 (1.3) | 4.0 (1.1) | 11.3 (1.5) | 3.9 (1.2) | 16.1 (1.4) | 20.0 (1.7) |
| **Shoulder rot ROM** | 9.6 (0.7) | 6.6 (1.7) | 18.0 (0.8) | 8.9 (1.7) | 26.9 (1.4) | 18.3 (1.5) | 13.3 (1.2) | 14.4 (1.0) |
| **Elbow flex-ext ROM** | 26.8 (3.9) | 17.4 (7.4) | 16.0 (2.6) | 6.2 (1.9) | 31.7 (1.7) | 27.4 (2.1) | 29.2 (2.2) | 43.9 (3.2) |

Table 5. 7: Shoulder and elbow ROMs (in degrees) for each subject while using the anatomical (A) and prosthetic (P) arm during reaching phase. Note, values in brackets represent ±1 SD.

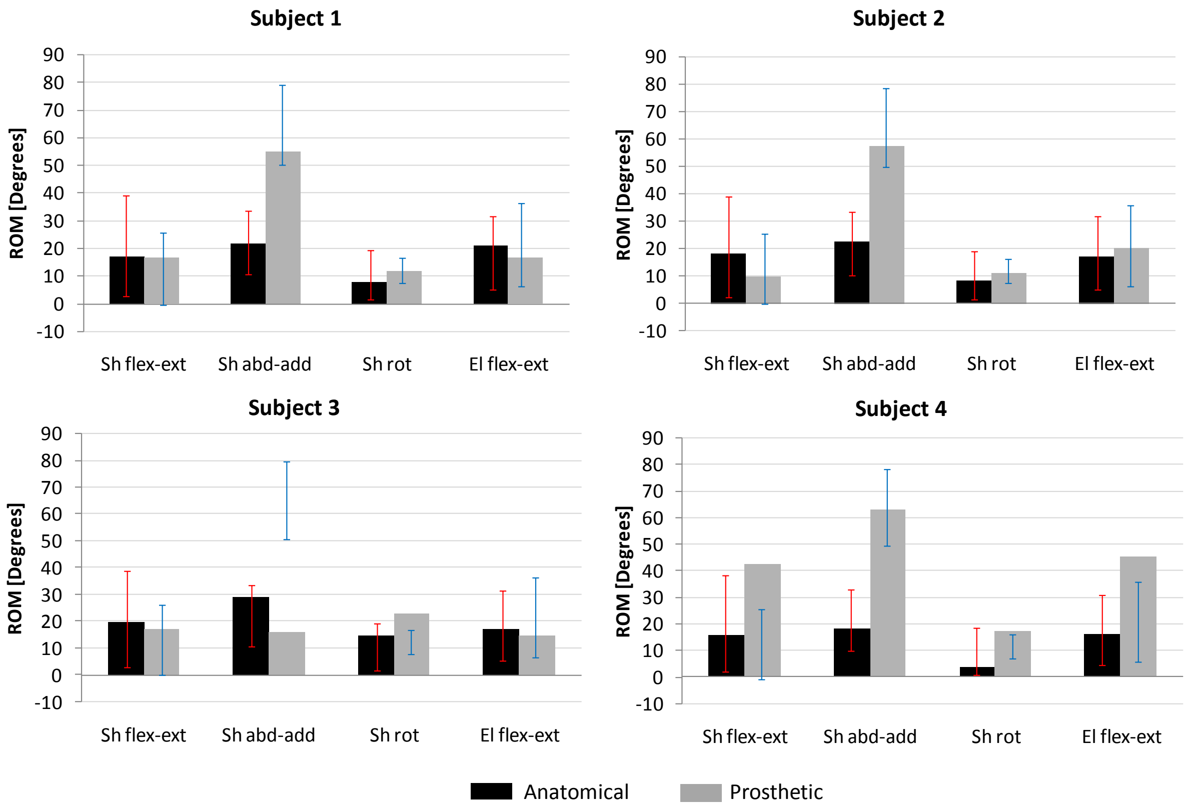



Figure 5. 11: Shoulder and elbow ROMs in manipulation phase during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | **Subject 1** | | **Subject 2** | | **Subject 3** | | **Subject 4** | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Shoulder flex-ext ROM** | 17.0 (5.5) | 16.5 (2.6) | 18.2 (1.8) | 9.8 (1.4) | 17.2 (2.5) | 20.2 (1.4) | 15.7 (2.1) | 42.6 (2.4) |
| **Shoulder abd-add ROM** | 21.7 (2.5) | 55.1 (2.3) | 22.7 (1.5) | 57.6 (1.6) | 28.9 (1.9) | 15.9 (2.0) | 18.0 (3.0) | 62.9 (1.7) |
| **Shoulder rot ROM** | 8.1 (1.9) | 12.0 (1.3) | 8.1 (0.9) | 10.9 (1.6) | 14.7 (1.8) | 22.9 (2.0) | 3.7 (0.6) | 17.4 (1.9) |
| **Elbow flex-ext ROM** | 20.9 (2.3) | 16.8 (4.6) | 17.2 (2.5) | 20.2 (1.4) | 17.2 (2.9) | 14.9 (3.2) | 16.0 (2.2) | 45.2 (3.5) |

Table 5. 8: Shoulder and elbow ROMs (in degrees) for each subject while using the anatomical (A) and prosthetic (P) arm during manipulation phase. Note, values in brackets represent ±1 SD.

#### 5.4.2.3. *Acceleration variability*

As visualisation of warping of 3D acceleration trajectories is difficult, for illustration purposes examples of X axis accelerations from two trials before and after time warping in reaching and manipulation phase are shown Figure 5. 12 and Figure 5. 13 respectively for subject 1. The mean temporal and magnitude variability results for both task phases together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes are shown in Figure 5. 14. Additionally, the mean values (and SD) temporal and magnitude variability results for both phases are listed in Table 5. 9.

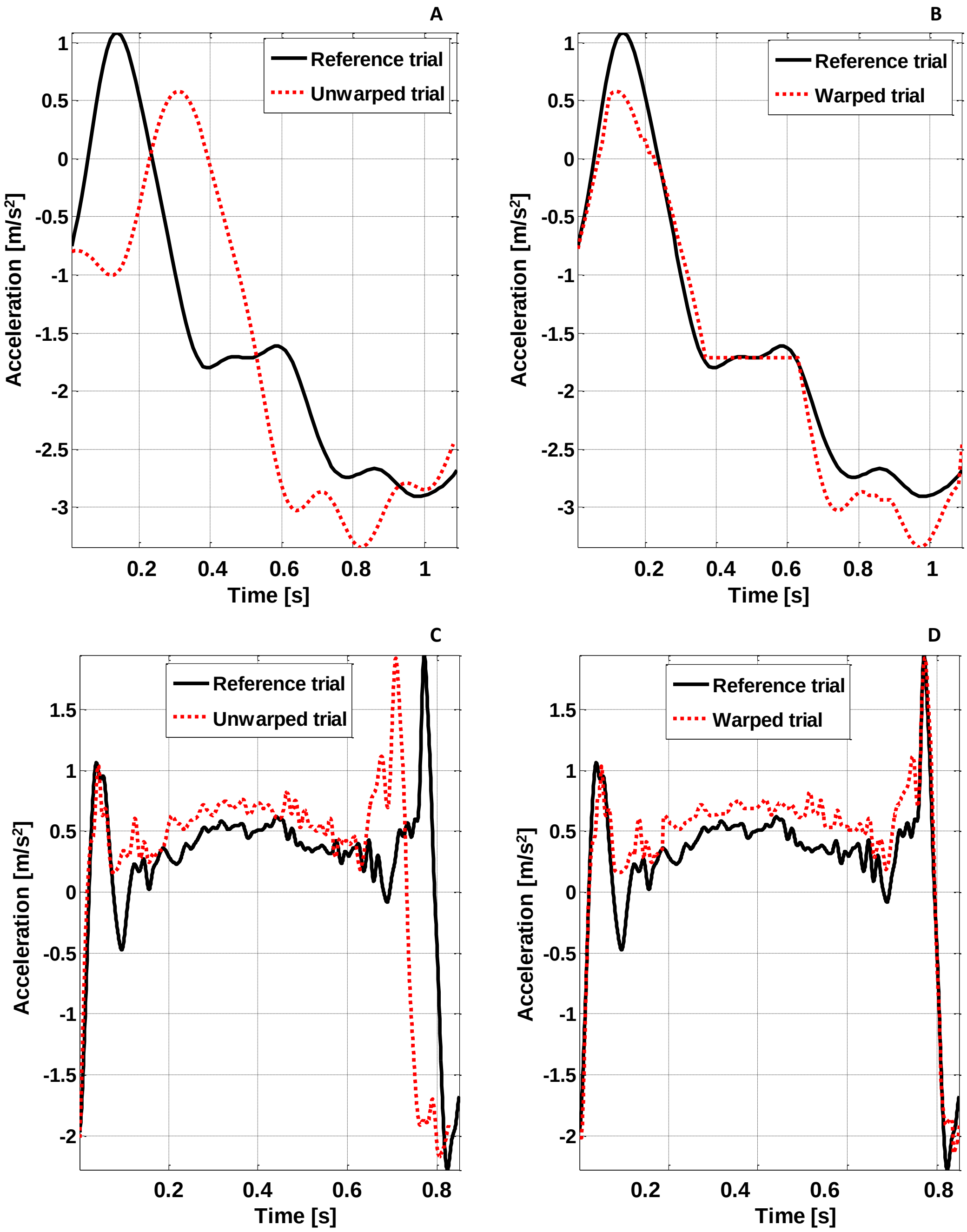



Figure 5. 12: Two examples of forearm-measured X axis acceleration before (A, and C) and after (B, and D) time warping during reaching (A and B) and manipulation (C and D) phase respectively using the anatomical arm (Subject 1).

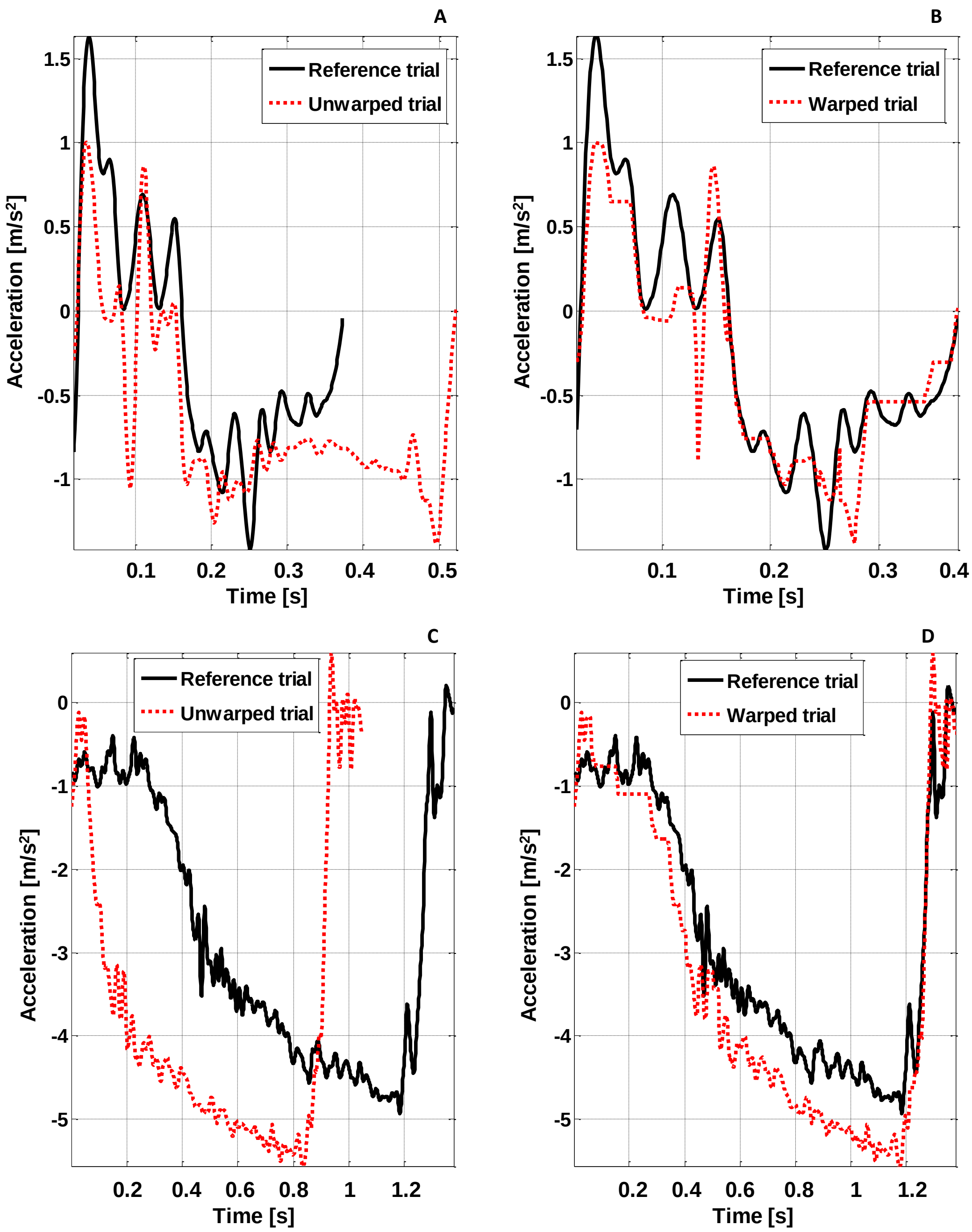



Figure 5. 13: Two examples of forearm acceleration in the X axis before (A, and C) and after (B, and D) time warping during the reaching (A and B) and manipulation (C and D) phase respectively using the prosthetic arm (Subject 1).

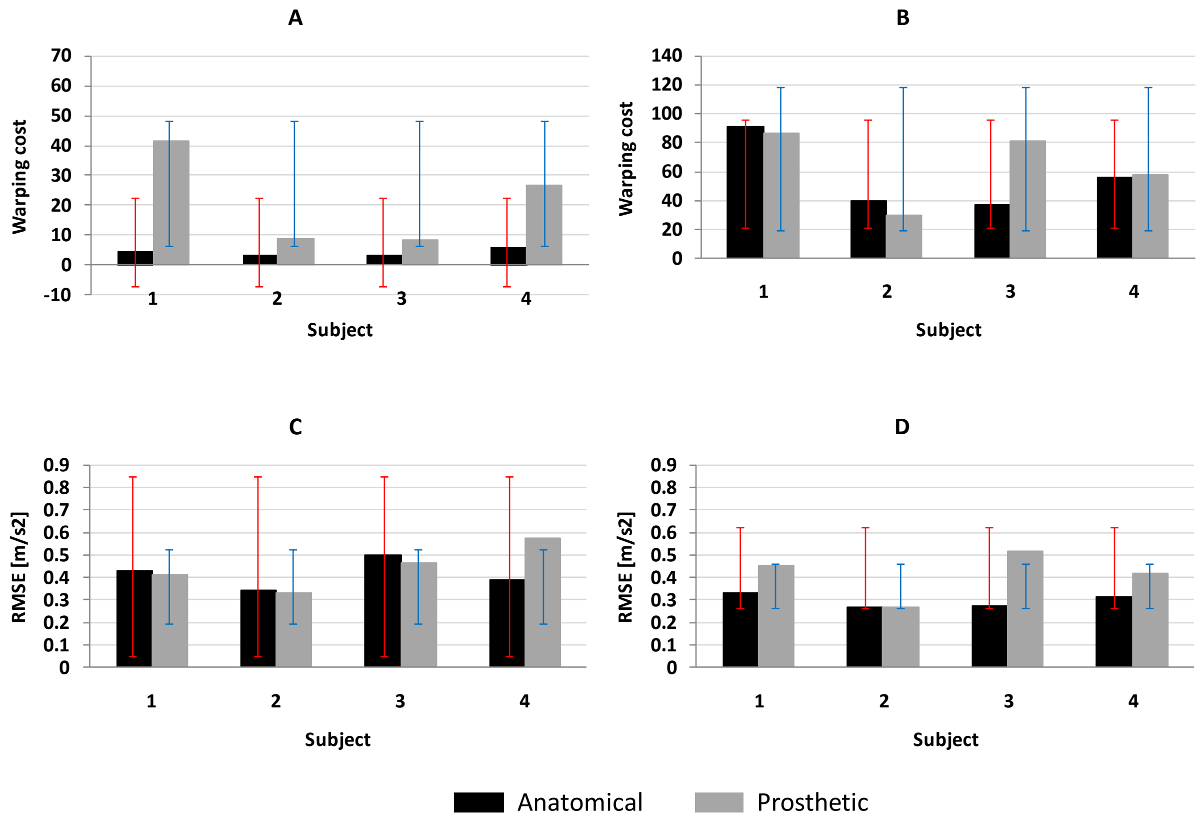



Figure 5. 14: Mean temporal variability in reaching (A) and manipulation (B) phase, and mean magnitude variability in reaching (C) and manipulation (D) phase during the anatomical hand use (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

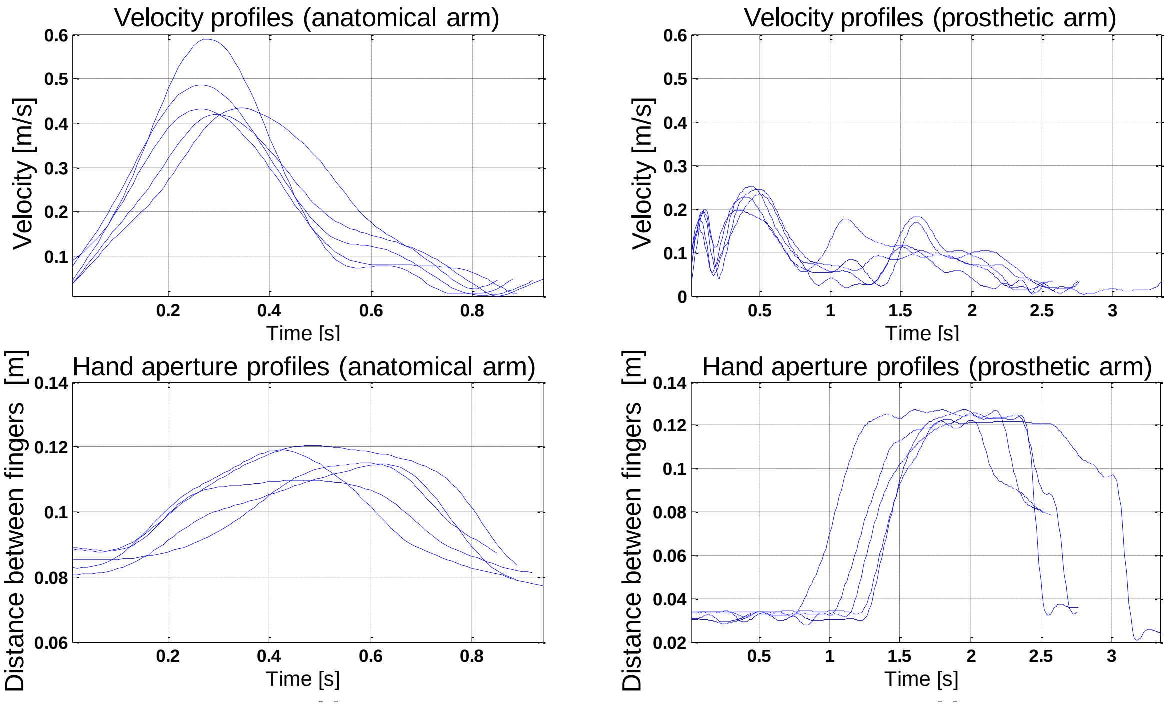
| | Subject 1 | | Subject 2 | | Subject 3 | | Subject 4 | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Warping cost (reaching phase)** | 4.81 (2.73) | 41.7 (27.1) | 3.49 (1.85) | 8.68 (4.24) | 3.57 (1.73) | 8.59 (5.42) | 5.94 (2.67) | 26.6 (10.7) |
| **Warping cost (manipulation phase)** | 91.1 (38.5) | 86.2 (25.7) | 39.6 (14.4) | 29.8 (13.7) | 37.5 (14.7) | 80.8 (35.9) | 56.3 (22.8) | 58.1 (28.6) |
| **RMSE (reaching phase)** | 0.43 (0.10) | 0.41 (0.11) | 0.34 (0.10) | 0.33 (0.08) | 0.50 (0.13) | 0.46 (0.18) | 0.39 (0.08) | 0.57 (0.11) |
| **RMSE (manipulation phase)** | 0.33 (0.08) | 0.45 (0.13) | 0.27 (0.07) | 0.27 (0.03) | 0.27 (0.03) | 0.51 (0.24) | 0.31 (0.10) | 0.42 (0.07) |

Table 5. 9: Mean warping cost (a unit-less measure of temporal variability) in reaching and manipulation phase, and mean RMSE (in $m/s^2$) calculated between reference and warped trials (measure of magnitude variability) in reaching and manipulation phase while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

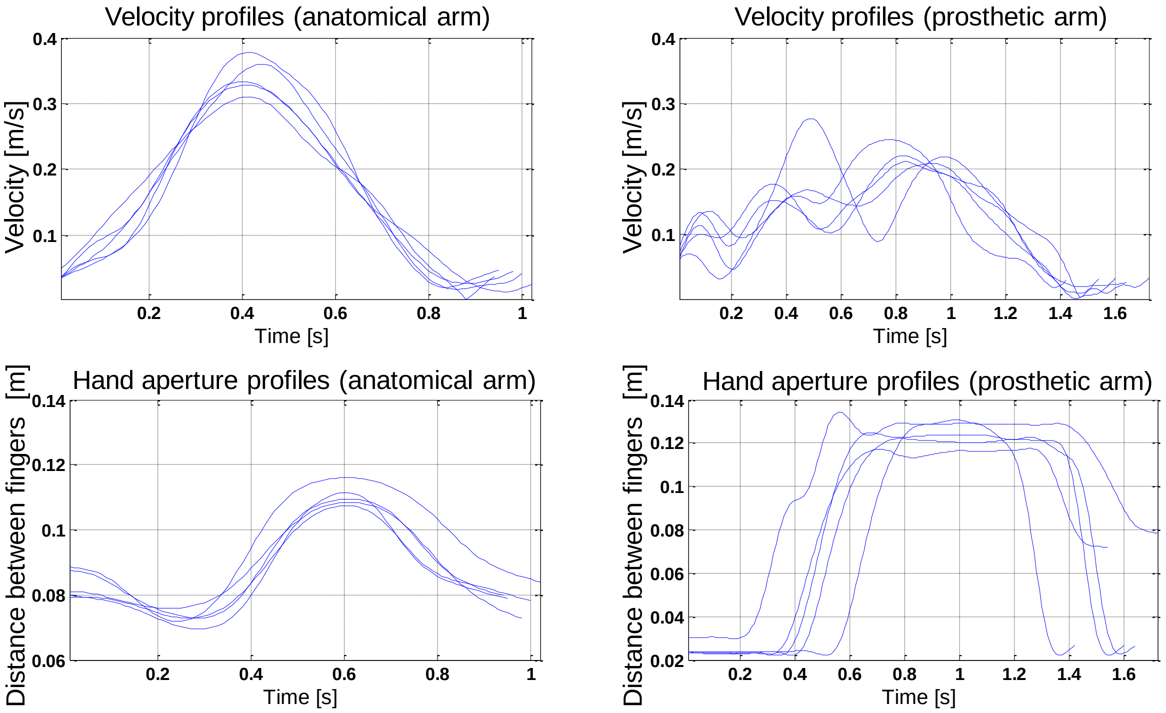
#### *5.4.2.4. Movement velocity and hand aperture during reaching phase*

Examples of hand aperture and wrist velocity profiles for are shown for all subjects in Figure 5. 15. Peak wrist joint velocity and time to peak velocity together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes are presented in Figure 5. 16 and listed in Table 5. 10. Times to peak aperture together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes are illustrated in Figure 5.17 and listed in Table 5. 11.

## Subject 1

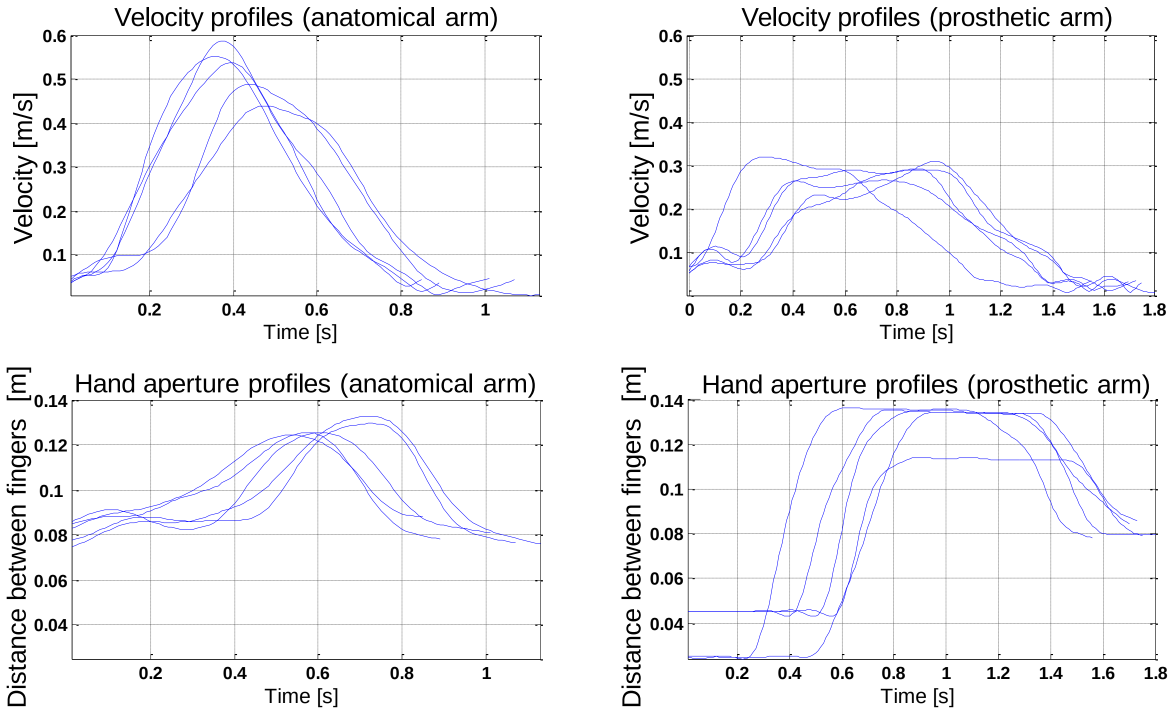



## Subject 2



Continued

## Subject 3




## Subject 4

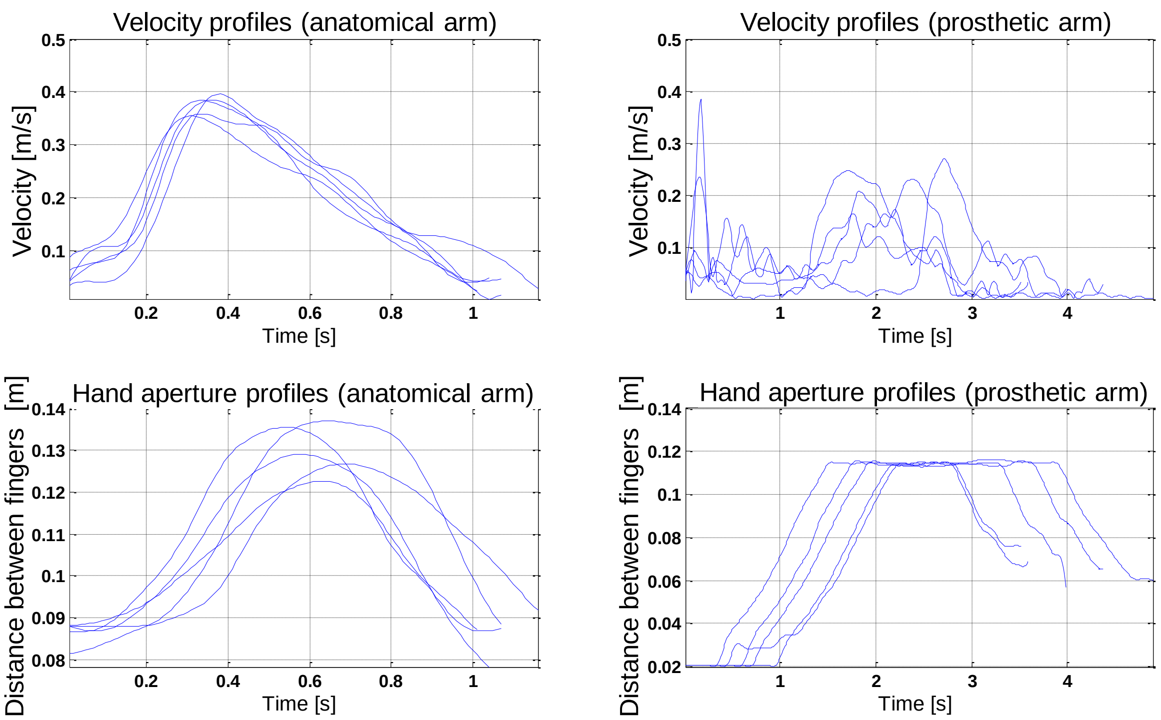



Figure 5. 15: Forearm velocity and hand aperture profiles while using the anatomical and prosthetic arm.

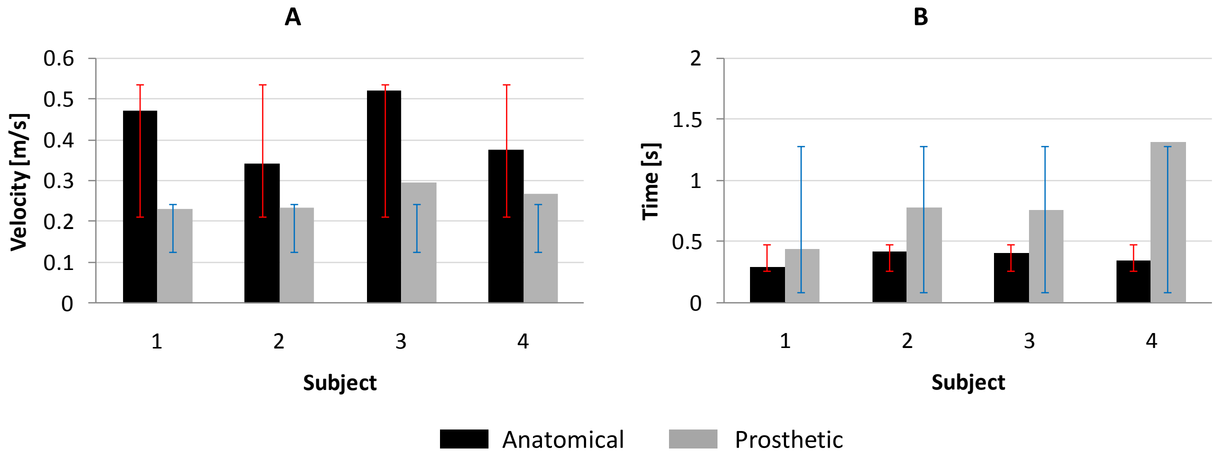



Figure 5. 16: Peak velocity (A) and time to peak velocity (B) measured at the wrist joint during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | **Subject 1** | | **Subject 2** | | **Subject 3** | | **Subject 4** | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Peak velocity** | 0.47 (0.07) | 0.23 (0.02) | 0.34 (0.03) | 0.23 (0.03) | 0.52 (0.06) | 0.29 (0.02) | 0.38 (0.02) | 0.27 (0.07) |
| **Time to peak velocity** | 0.3 (0.0) | 0.4 (0.1) | 0.4 (0.0) | 0.8 (0.2) | 0.4 (0.1) | 0.8 (0.3) | 0.3 (0.0) | 1.3 (1.1) |

Table 5. 10: Peak velocity (in m/s) and time to peak velocity (in seconds) measured at the wrist joint while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

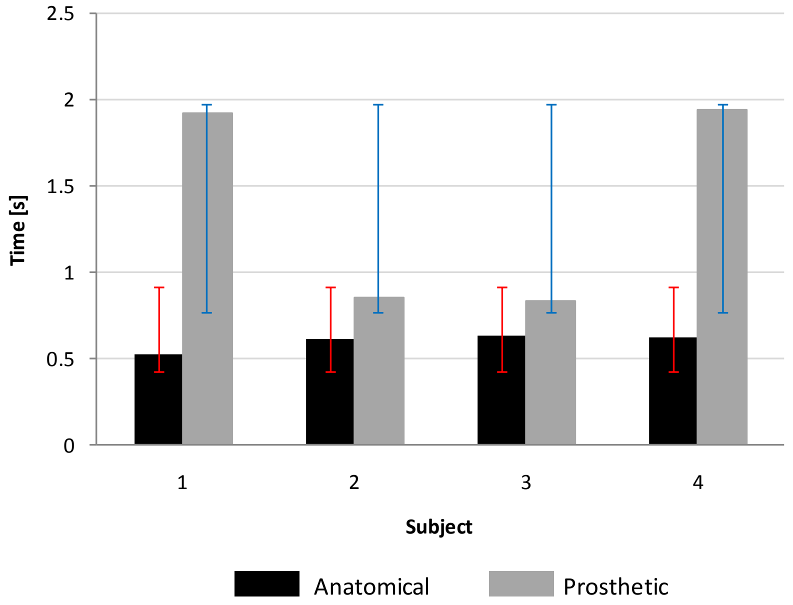



Figure 5.17: Time to peak aperture during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | **Subject 1** | | **Subject 2** | | **Subject 3** | | **Subject 4** | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Time to peak aperture [s]** | 0.5 (0.1) | 1.9 (0.1 | 0.6 (0.0) | 0.9 (0.3) | 0.6 (0.1) | 0.8 (0.1) | 0.6 (0.1) | 1.9 (0.3) |

Table 5. 11: Time to peak aperture (in seconds) while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

### *5.4.3. Gaze behaviours*

Figure 5. 18 and Figure 5. 19 provide gaze sequence of gaze data gathered for all subjects while using the anatomical and prosthetic arm.

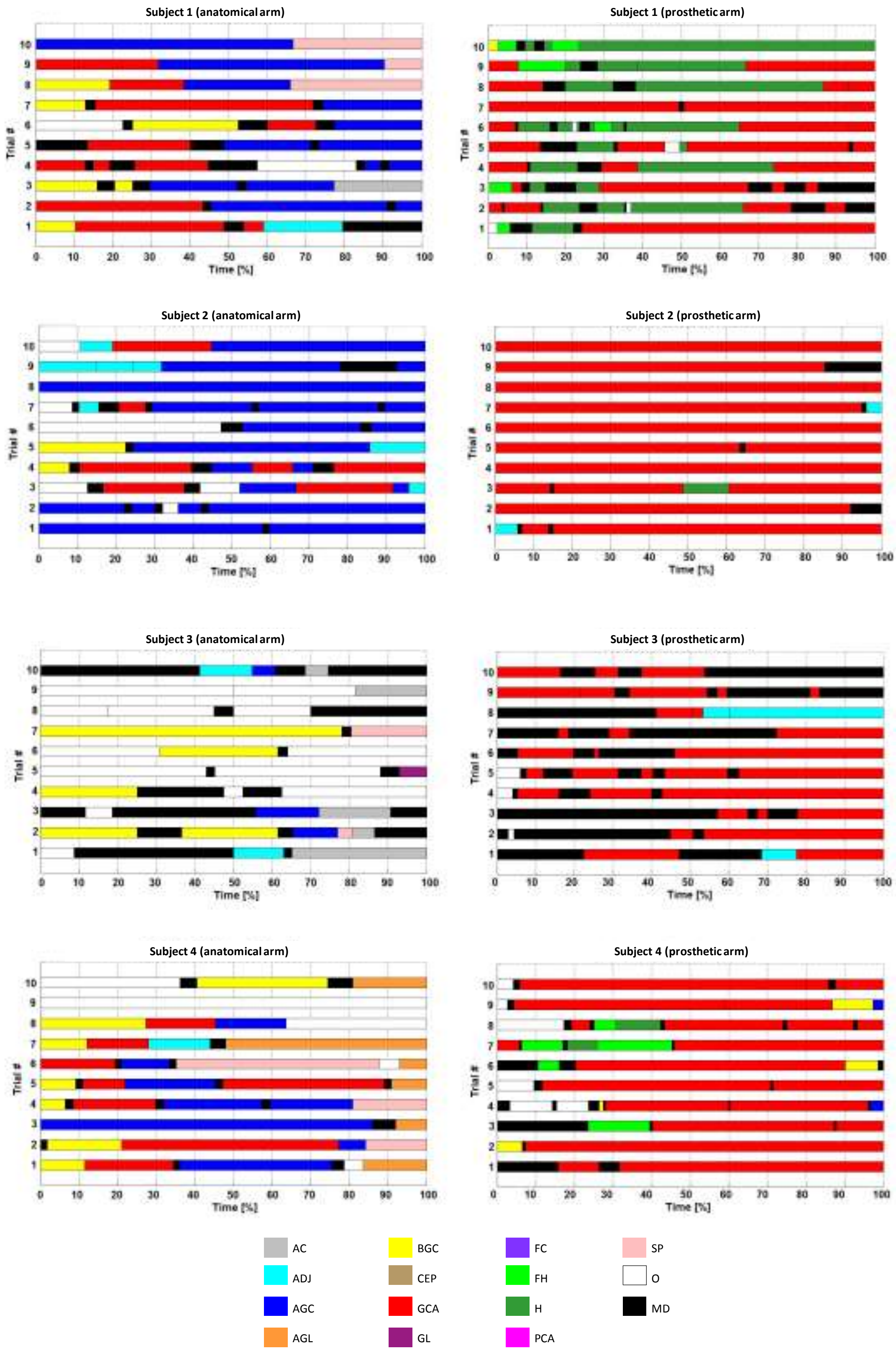



Figure 5. 18: Trial by trial gaze sequence for all subjects during reaching phase. The trial number is represented on the vertical axis. The horizontal axis represents the task duration normalised to 100%. The gaze fixation sequence in a given trial is presented in a stacked bar in which each coloured segment denotes a gaze fixation at a particular AOI, the length of each coloured segment corresponds to the duration of the fixation at the AOI.

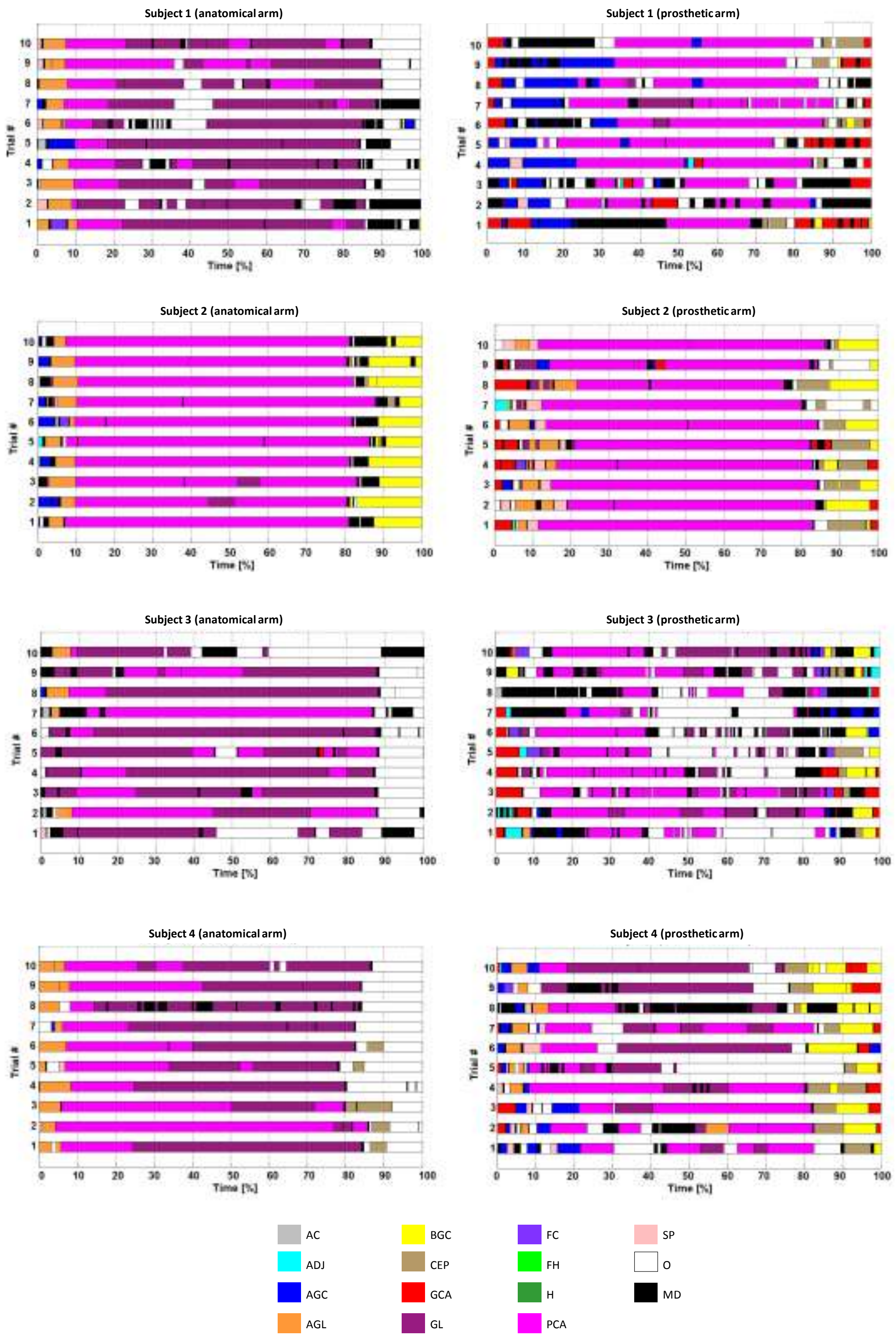



Figure 5. 19: Trial by trial gaze sequence for all subjects during manipulation phase. The trial number is represented on the vertical axis. The horizontal axis represents the task duration normalised to 100%. The gaze fixation sequence in a given trial is presented in a stacked bar in which each coloured segment denotes a gaze fixation at a particular AOI, the length of each coloured segment corresponds to the duration of the fixation at the AOI.

The number of transitions that subjects made between AOIs during reaching and manipulation phase together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes is presented in Figure 5. 20 and listed in Table 5. 12.

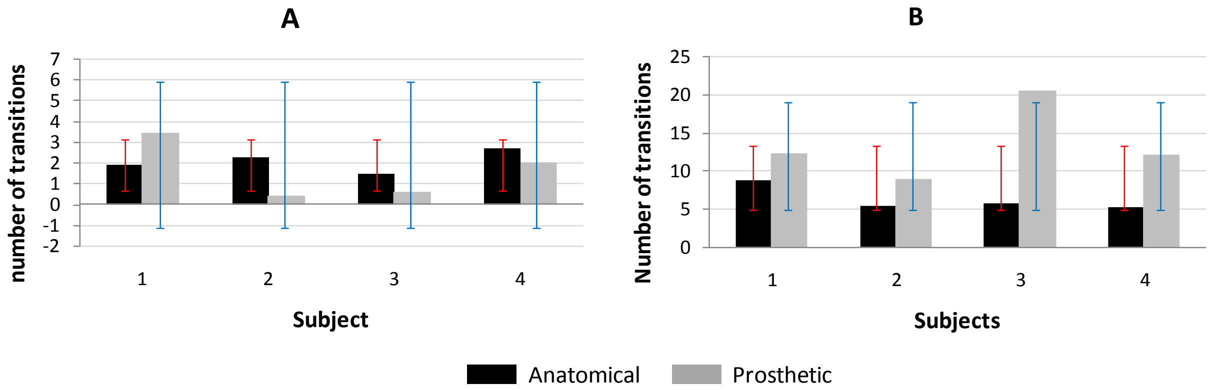



Figure 5. 20: Mean of number of transitions between AOIs in reaching (A) and in manipulation (B) phase during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | Subject 1 | | Subject 2 | | Subject 3 | | Subject 4 | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Number of transitions (reaching phase)** | 1.9 (0.7) | 3.4 (1.7 | 2.3 (2.0) | 0.4 (0.7) | 1.5 (0.9) | 0.6 (0.7) | 2.7 (1.3) | 2.0 (1.1) |
| **Number of transitions (manipulation phase)** | 8.8 (2.1) | 12.2 (3.8) | 5.4 0.8) | 8.9 (1.7) | 5.7 (1.8) | 20.5 (4.4) | 5.2 (2.0) | 12.0 (3.4) |

Table 5. 12: Mean of number of gaze transitions between AOIs during reaching and manipulation phase while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

Figure 5. 21 and Figure 5. 22 show the averaged fixation duration that each subject made at each AOI together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes during the reaching and manipulation phase respectively. The averaged fixation duration values (and SD) that each subject made at each AOI during the reaching and manipulation phase are listed in Table 5. 13 and Table 5. 14 respectively. The group mean of averaged gaze fixation for both phases

together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes is illustrated in Figure 5. 23 and reported in Table 5. 15.

The averaged gaze duration during reach at aggregated AOIs, as introduced in Chapter 4, together with CI taken from Chapter 4 for V1 (baseline, anatomical hand) and V4 (last session, prosthesis), provided for comparison purposes is shown in Figure 5. 24 and Table 5. 16 for each subject and for the group mean in Figure 5. 25 and Table 5. 17.

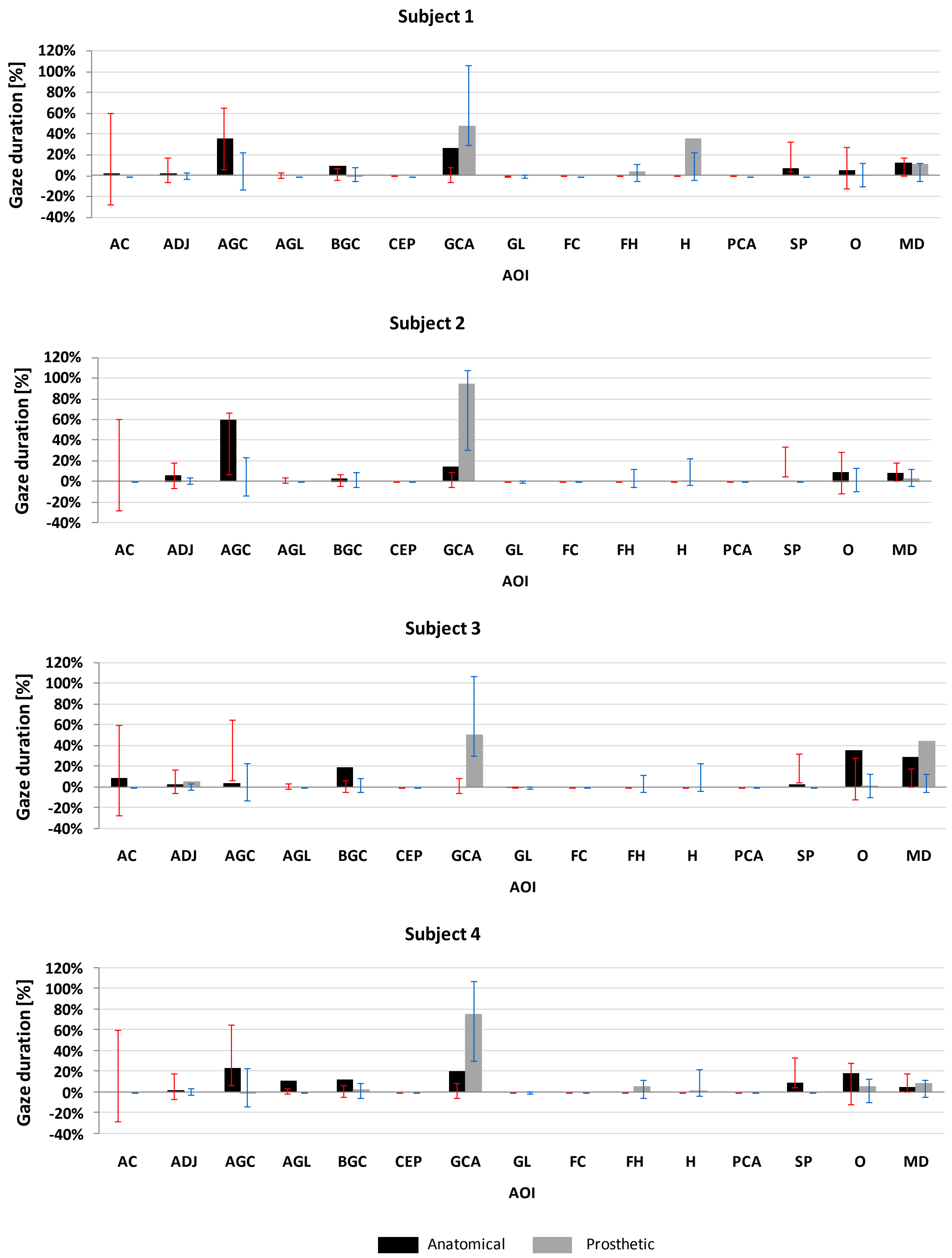



Figure 5. 21: Subject by subject averaged gaze in reaching phase during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | Subject 1 | | Subject 2 | | Subject 3 | | Subject 4 | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **AC** | 2.3 (7.2) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 8.2 (11.8) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **ADJ** | 2.1 (6.5) | 0.0 (0.0) | 6.2 (9.7) | 1.0 (2.1) | 2.7 (5.6) | 5.4 (14.1) | 1.6 (5.1) | 0.0 (0.0) |
| **AGC** | 35.6 (21.1) | 0.0 (0.0) | 59.8 (29.6) | 0.0 (0.0) | 3.4 (6.0) | 0.0 (0.0) | 23.3 (27.5) | 0.6 (1.3) |
| **AGL** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 11.2 (16.0) | 0.0 (0.0) |
| **BGC** | 8.9 (10.5) | 0.3 (0.8) | 3.0 (7.3) | 0.0 (0.0) | 18.4 (27.5) | 0.0 (0.0) | 11.9 (11.7) | 2.6 (4.1) |
| **CEP** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **GCA** | 26.8 (19.0) | 48.1 (28.2) | 14.0 (23.0) | 94.8 (5.4) | 0.0 (0.0) | 50.0 (21.7) | 20.6 (20.0) | 74.8 (13.4) |
| **GL** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.7 (2.3) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **FC** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **FH** | 0.0 (0.0) | 3.8 (4.8) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 5.8 (10.0) |
| **H** | 0.0 (0.0) | 35.5 (26.3) | 0.0 (0.0) | 1.2 (3.7) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 1.9 (4.1) |
| **PCA** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **SP** | 7.5 (13.6) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 2.3 (6.2) | 0.0 (0.0) | 8.8 (17.1) | 0.0 (0.0) |
| **O** | 4.8 (10.2) | 0.9 (1.3) | 9.3 (15.2) | 0.0 (0.0) | 35.2 (35.6) | 1.1 (2.1) | 18.0 (31.6) | 5.3 (7.5) |
| **MD** | 12.1 (9.9) | 11.5 (10.4) | 7.7 (5.6) | 3.1 (4.6) | 29.2 (25.2) | 43.5 (18.3) | 4.7 (2.7) | 9.0 (8.6) |

Table 5. 13: Subject by subject averaged gaze duration (normalised to 100%) during reaching phase while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

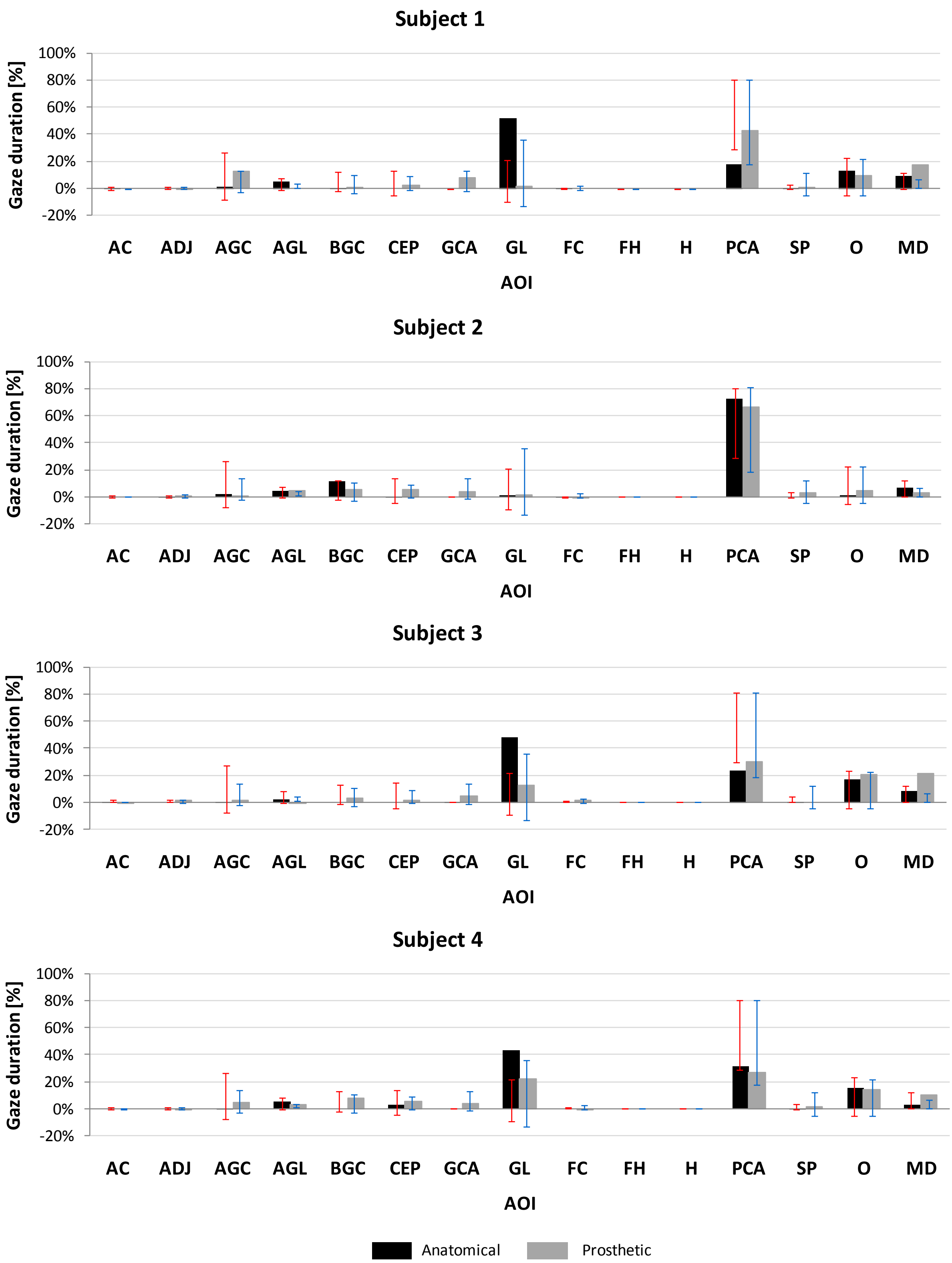



Figure 5. 22: Subject by subject averaged gaze duration in manipulation phase during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | Subject 1 | | Subject 2 | | Subject 3 | | Subject 4 | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **AC** | 0.2 (0.7) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.3 (0.6) | 0.2 (0.5) | 0.0 (0.0) | 0.0 (0.0) |
| **ADJ** | 0.0 (0.0) | 0.2 (0.6) | 0.2 (0.4) | 0.4 (1.1) | 0.0 (0.0) | 1.5 (1.4) | 0.0 (0.0) | 0.1 (0.2) |
| **AGC** | 1.2 (2.2) | 12.7 (5.3) | 1.7 (1.9) | 0.8 (1.4) | 0.1 (0.4) | 1.9 (2.9) | 0.1 (0.3) | 4.4 (3.2) |
| **AGL** | 5.2 (2.3) | 0.0 (0.0) | 4.6 (1.7) | 4.3 (2.9) | 1.6 (2.3) | 0.2 (0.6) | 5.3 (2.3) | 3.3 (2.3) |
| **BGC** | 0.2 (0.3) | 0.6 (1.0) | 11.8 (3.2) | 5.8 (4.6) | 0.0 (0.0) | 3.6 (2.8) | 0.0 (0.0) | 8.2 (3.9) |
| **CEP** | 0.0 (0.0) | 2.8 (3.2) | 0.5 (0.8) | 5.8 (3.9) | 0.0 (0.0) | 1.8 (2.3) | 2.8 (3.8) | 5.5 (3.6) |
| **GCA** | 0.0 (0.0) | 8.3 (6.0) | 0.0 (0.0) | 4.1 (3.5) | 0.1 (0.4) | 4.8 (4.1) | 0.0 (0.0) | 3.5 (2.8) |
| **GL** | 51.7 (8.1) | 2.0 (4.5) | 1.5 (2.7) | 1.7 (2.0) | 48.3 (23.7) | 12.4 (10.0) | 42.7 (17.6) | 22.3 (17.1) |
| **FC** | 0.4 (1.3) | 0.0 (0.0) | 0.2 (0.7) | 0.3 (0.8) | 0.0 (0.0) | 2.0 (2.0) | 0.0 (0.0) | 0.3 (0.8) |
| **FH** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **H** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **PCA** | 17.7 (12.1) | 43.3 (11.0) | 72.2 (4.3) | 66.2 (6.0) | 23.1 (23.7) | 29.8 (9.8) | 31.1 (20.3) | 26.9 (19.0) |
| **SP** | 0.7 (1.0) | 0.7 (1.3) | 0.0 (0.0) | 2.8 (1.9) | 0.2 (0.5) | 0.0 (0.0) | 0.2 (0.5) | 1.7 (1.4) |
| **O** | 13.2 (4.9) | 9.5 (3.7) | 0.9 (0.4) | 4.7 (5.4) | 17.0 (10.7) | 20.7 (11.8) | 15.5 (4.7) | 13.8 (13.9) |
| **MD** | 9.4 (6.6) | 17.4 (10.6) | 6.5 (2.9) | 3.1 (1.8) | 8.2 (7.5) | 21.3 (10.9) | 2.3 (4.6) | 10.2 (14.1) |

Table 5. 14: Subject by subject averaged gaze duration (normalised to 100%) during manipulation phase while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

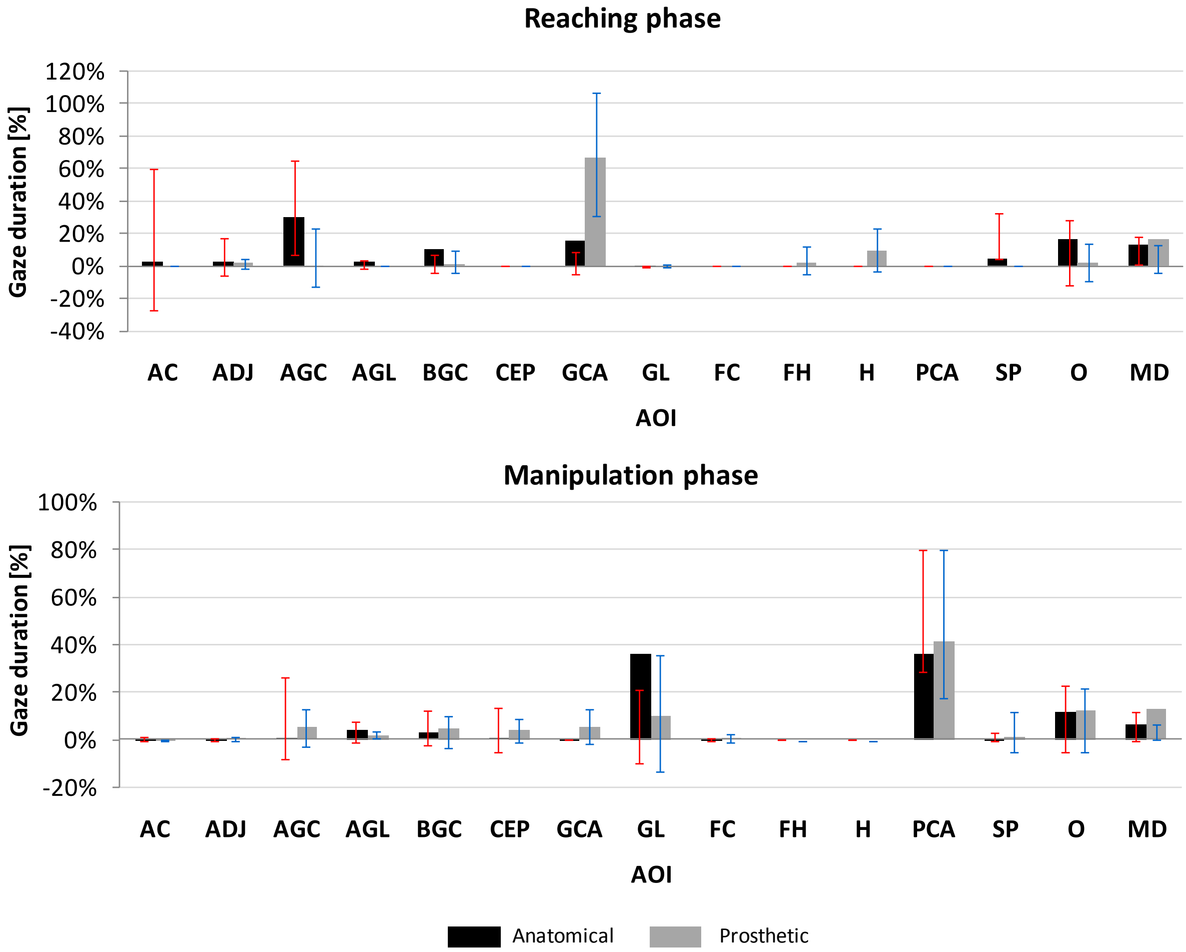



Figure 5. 23: The group mean of the averaged gaze duration using their anatomical and prosthetic arm in reaching and in manipulation phase separately while anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| Phase | Reaching phase | | Manipulation phase | |
|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** |
| **AC** | 2.6 (3.9) | 0.0 (0.0) | 0.1 (0.2) | 0.0 (0.1) |
| **ADJ** | 3.1 (2.1) | 1.6 (2.6) | 0.0 (0.1) | 0.6 (0.7) |
| **AGC** | 30.5 (23.6) | 0.2 (0.3) | 0.8 (0.8) | 5.0 (5.4) |
| **AGL** | 2.8 (5.6) | 0.0 (0.0) | 4.2 (1.7) | 2.0 (2.2) |
| **BGC** | 10.6 (6.4) | 0.7 (1.3) | 3.0 (5.9) | 4.6 (3.2) |
| **CEP** | 0.0 (0.0) | 0.0 (0.0) | 0.8 (1.3) | 4.0 (2.0) |
| **GCA** | 15.4 (11.5) | 66.9 (22.2) | 0.0 (0.1) | 5.2 (2.1) |
| **GL** | 0.2 (0.4) | 0.0 (0.0) | 36.1 (23.4) | 9.6 (9.8) |
| **FC** | 0.0 (0.0) | 0.0 (0.0) | 0.2 (0.2) | 0.6 (0.9) |
| **FH** | 0.0 (0.0) | 2.4 (2.9) | 0.0 (0.0) | 0.0 (0.0) |
| **H** | 0.0 (0.0) | 9.7 (17.3) | 0.0 (0.0) | 0.0 (0.0) |
| **PCA** | 0.0 (0.0) | 0.0 (0.0) | 36.0 (24.7) | 41.5 (18.0) |
| **SP** | 4.6 (4.2) | 0.0 (0.0) | 0.3 (0.3) | 1.3 (1.2) |
| **O** | 16.8 (13.4) | 1.8 (2.4) | 11.7 (7.3) | 12.2 (6.8) |
| **MD** | 13.4 (10.9) | 16.8 (18.2) | 6.6 (3.1) | 13.0 (8.0) |

Table 5. 15: The group mean of the averaged gaze duration (normalised to 100%) using their anatomical (A) and prosthetic (P) arm during reaching and manipulation phase. Note, values in brackets represent ±1 SD.

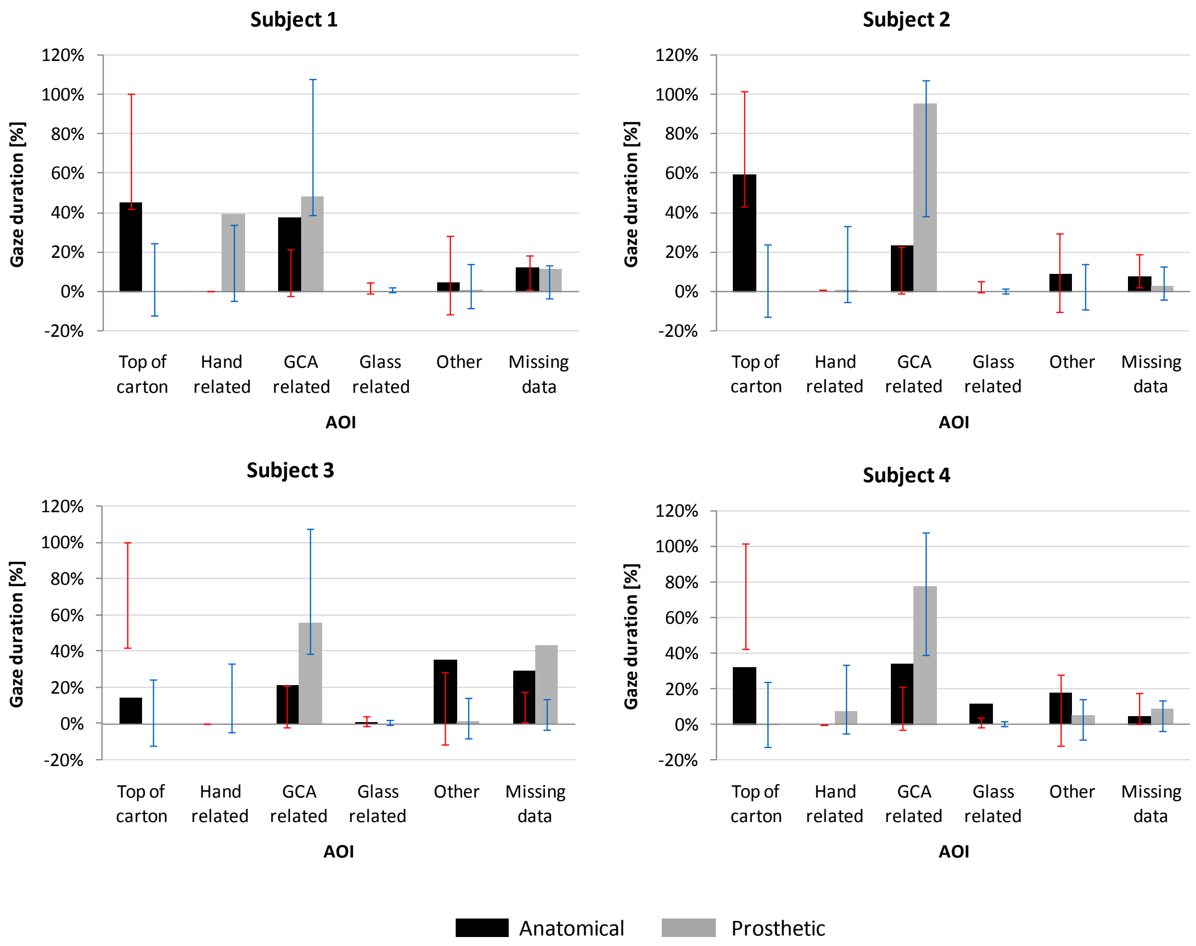



Figure 5. 24: Subject by subject averaged gaze duration for aggregated AOIs during reaching phase while anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| | Subject 1 | | Subject 2 | | Subject 3 | | Subject 4 | |
|---|---|---|---|---|---|---|---|---|
| **Arm** | **A** | **P** | **A** | **P** | **A** | **P** | **A** | **P** |
| **Top of carton** | 45.4 (29.8) | 0.0 (0.0) | 59.8 (29.6) | 0.0 (0.0) | 13.9 (14.0) | 0.0 (0.0) | 32.0 (31.0) | 0.6 (1.3) |
| **Hand related** | 0.0 (0.0) | 39.3 (28.4) | 0.0 (0.0) | 1.2 (3.7) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 7.7 (12.6) |
| **GCA related** | 37.8 (21.8) | 48.4 (27.7) | 23.3 (25.0) | 95.7 (5.4) | 21.0 (26.0) | 55.4 (16.8) | 34.1 (24.2) | 77.4 (15.0) |
| **Glass related** | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.7 (2.3) | 0.0 (0.0) | 11.2 (16.0) | 0.0 (0.0) |
| **Other** | 4.8 (10.2) | 0.9 (1.3) | 9.3 (15.2) | 0.0 (0.0) | 35.2 (35.6) | 1.1 (2.1) | 18.0 (31.6) | 5.3 (7.5) |
| **Missing data** | 12.1 (9.9) | 11.5 (10.4) | 7.7 (5.6) | 3.1 (4.6) | 29.2 (25.2) | 43.5 (18.3) | 4.7 (2.7) | 9.0 (8.6) |

Table 5. 16: Subject by subject averaged gaze duration (normalised to 100%) for aggregated AOIs during reaching phase while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

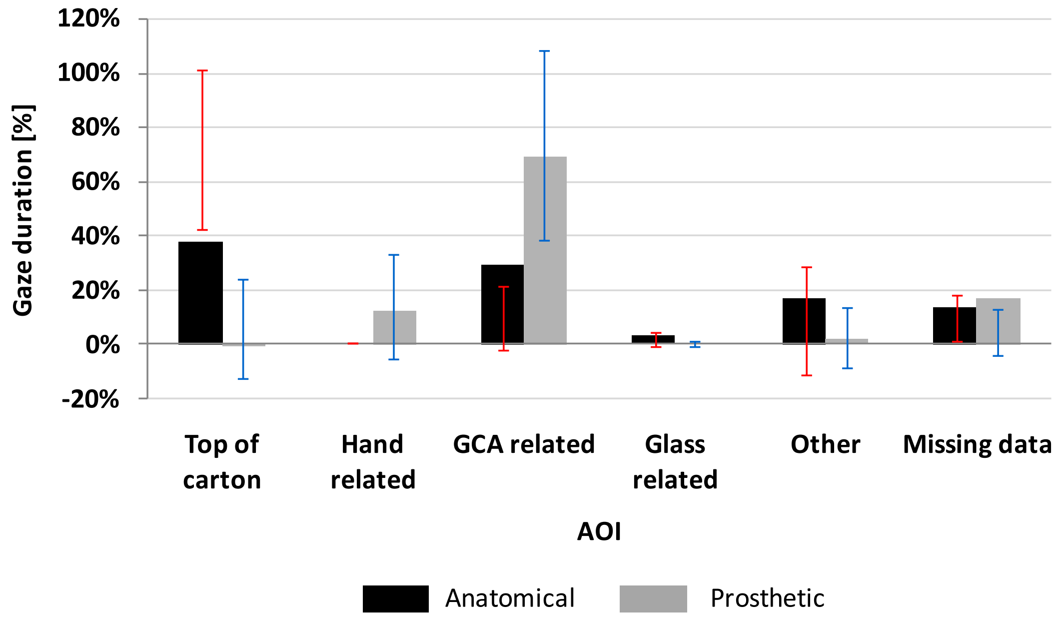



Figure 5. 25: The group mean of the averaged gaze duration for aggregated AOIs in reaching during anatomical (black bars) and prosthetic (gray bars) arm use (amputee subjects). Note, the error bars represent upper and lower CIs of the mean values obtained at V1 (baseline – shown in red) and V4 (final evaluation with prosthesis – shown in blue) calculated from the experiment reported in Chapter 4 (anatomically intact subjects).

| Arm | A | P |
|---|---|---|
| **Top of carton** | 37.8 (19.5) | 0.2 (0.3) |
| **Hand related** | 0.0 (0.0) | 12.0 (18.5) |
| **GCA related** | 29.1 (8.2) | 69.2 (21.6) |
| **Glass related** | 3.0 (5.5) | 0.0 (0.0) |
| **Other** | 16.8 (13.4) | 1.8 (2.4) |
| **Missing data** | 13.4 (10.9) | 16.8 (18.2) |

Table 5. 17: The group mean of the averaged gaze duration (normalised to 100%) for aggregated AOIs during reaching while using the anatomical (A) and prosthetic (P) arm. Note, values in brackets represent ±1 SD.

### *5.4.4. The correlation between clinical evaluation tools and measures of skill*

The correlations of the subject's ranking based on each of the skill measures that were evidently indicative of learning in Chapter 4 with their ranking based on SHAP functionality index are illustrated in Figure 5. 26, and with their responses to OPUS and TAPES are illustrated Figure 5. 27. Additionally, the relationships between other metrics that changed when the prosthesis was introduced but did not show statistical significance over practice with SHAP functionality index are illustrated in Figure 5. 28. Their relationships with OPUS and TAPES results are illustrated Figure 5. 29.

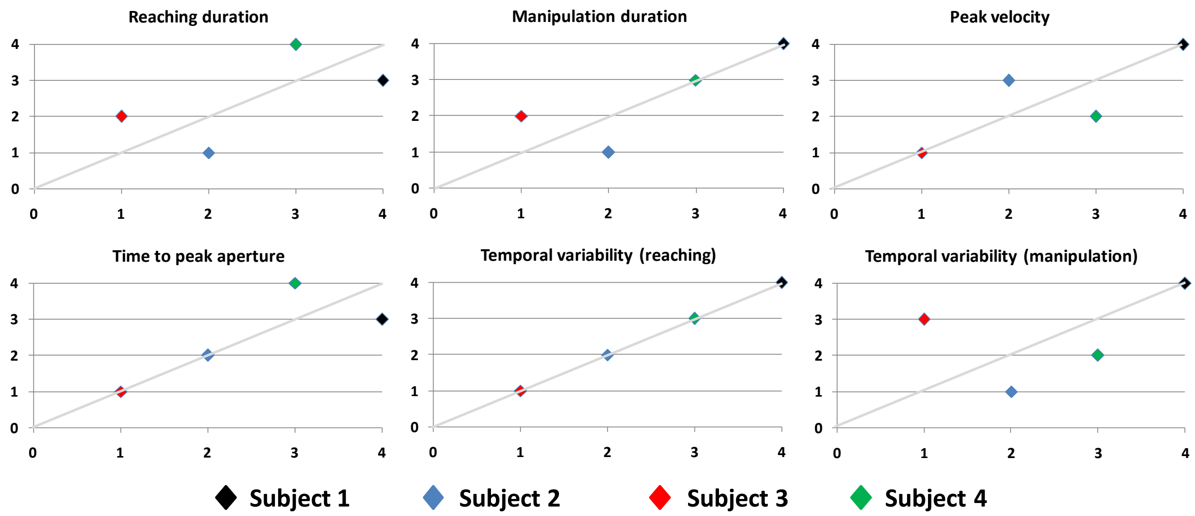



Figure 5. 26: The correlation between the subject's rank based on SHAP (X axis) and measures of skill (Y axis) that showed statistically significant changes with learning in Chapter 4. Note, the diagonal line represents perfect correlation between the two variables (Y = X).

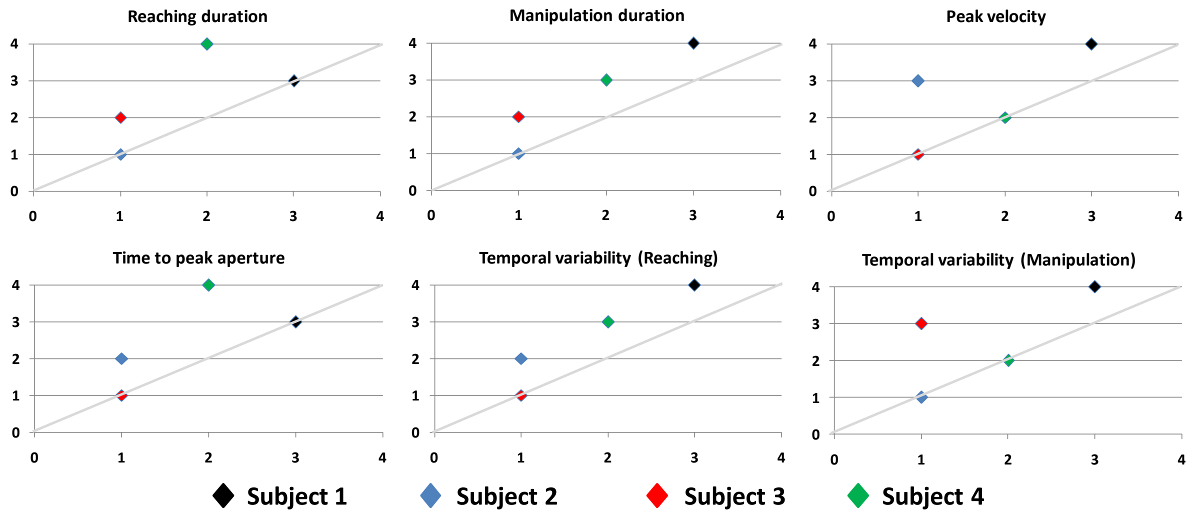



Figure 5. 27: The correlation between the subject's rank based on OPUS and TAPES (X axis) and measures of skill (Y axis) that showed statistically significant changes with learning in Chapter 4.

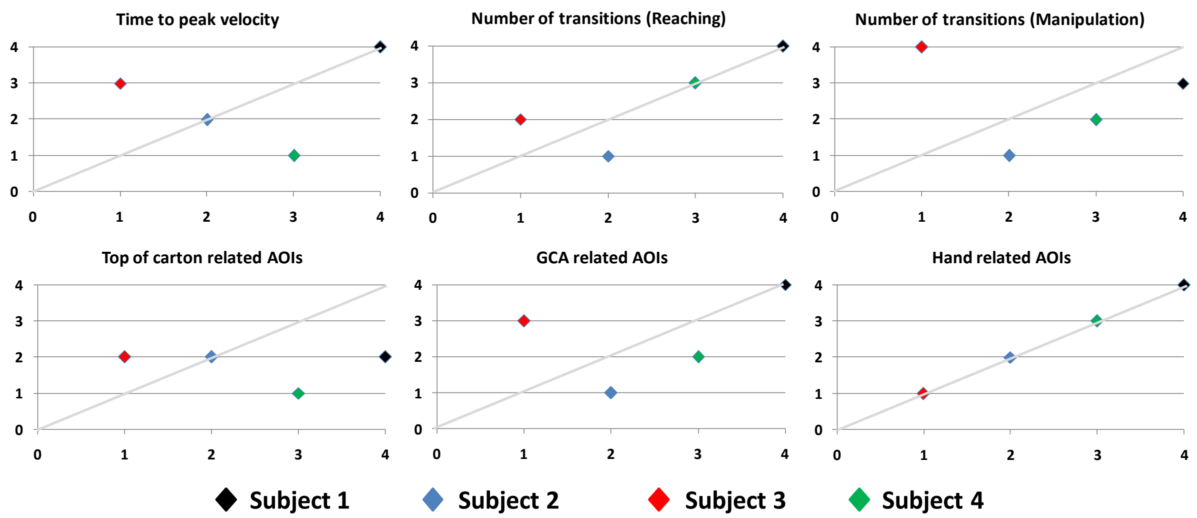



Figure 5. 28: The correlation between the subjects' ranking based on SHAP (X axis) and measures of skill (Y axis) that changed with introducing the prosthesis but did not reach significance with learning in Chapter 4.

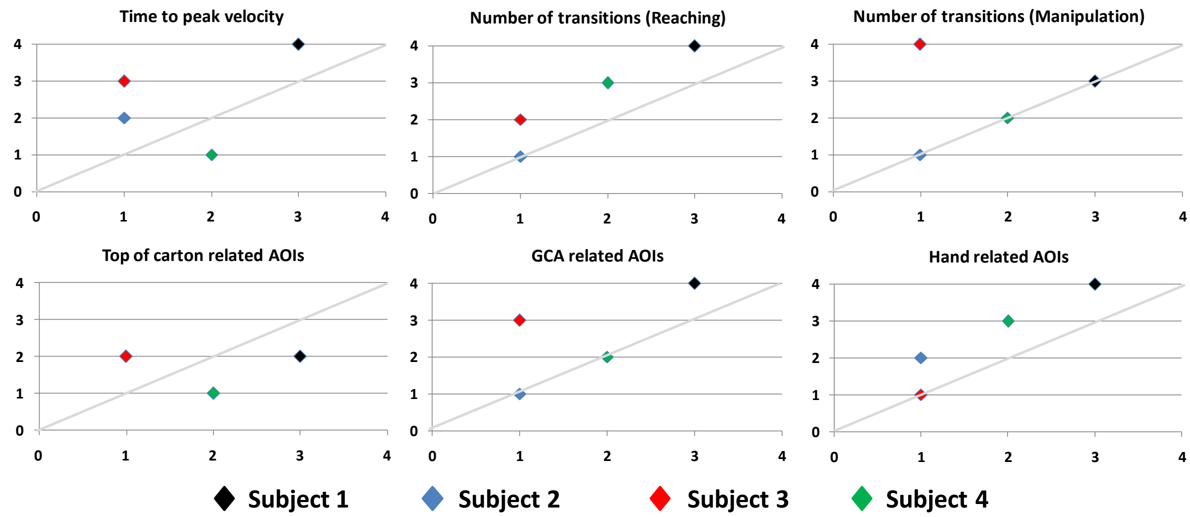



Figure 5. 29: The correlation between the subject's rank based on OPUS and TAPES (X axis) and measures of skill (Y axis) that changed with introducing the prosthesis but did not show. Note, in the "Top of carton related AOIs" graph, both subjects 2 and 3 had the same ranking thus their data points overlap.

## 5.5. Discussion

### *5.5.1. Upper limb prosthesis clinical evaluation tools*

#### *5.5.1.1. The OPUS and TAPES*

All 4 subjects in the study are well established users of myoelectric prostheses who reported wearing their prosthesis for at least 14 hrs/day and were considered by their OT to be "very good" prosthesis users. Their scores in the functional status module of OPUS largely support this observation. All subjects rated their performance of most of the items in this module as being "easy" or "very easy" and this resulted in overall scores of between 3.2 and 3.8 (Table 5. 3). This result indicates that all four have a functional status score well above the average for the amputee population (zero) (110). A prosthesis can be used to actively perform a task, or passively in support of the anatomical arm performing the task. Although the UEFS module includes questions asking the subject whether the prosthesis is normally used to perform each of the listed tasks, this information is not considered when calculating the functional status score. This makes interpretation of the results of OPUS challenging. For instance, subject 2, whose functional status is estimated to be 3.8, reported all 19 items in UEFS module "very easy" to perform, however, he reported performing only 9 out of the 19 items (Table 5. 4) using his prosthesis. By contrast, subject 4, who scored lower on his functional status (3.2) and found three items to be either "difficult" or "easy" to perform, reported performing 13 out of the 19 items using the prosthesis. It could be argued, therefore, that UEFS scores the consequences of amputation on amputee's quality of life and provides only indirect information on the functional gains from using their prosthesis.

The overall impression that all 4 subjects appear to be very well adjusted to their prosthesis and amputation also emerges from the TAPES scores. Although they are aware of the limitations of their prosthesis, they are generally well satisfied with their device. Apart from their amputation, they did not report any physical problems or pain. All amputees reported being either full-time employed or self-employed. Therefore, it could be assumed that all are emotionally and socially adapted to their amputation/prosthesis, as supported by their responses to TAPES. Only a small number of activities were found to be slightly restricted because of the prosthesis; for subjects 1 and 4 (carrying heavy objects and indulging in leisure and sport activities) and subjects 2 and 3 reported no restrictions. However, TAPES does not ask subjects to give reasons for why activities are restricted nor to report the particular activities that are restricted. Therefore, it is difficult to draw further conclusions from these results.

Both OPUS and TAPES did not evaluate the remaining anatomical arm; hence, their results cannot be compared to the amputee's remaining anatomical hand performance. Furthermore, both tools, interestingly, could not differentiate between the performance of subjects 2 and 3. Probably because both subjects are, as will be discussed shortly, are highly competent skilled users. However, both OPUS and TAPES highlighted the superiority of these two subjects to the other two subjects (1 and 4) and also showed small, but consistent differences between subjects 1 and 4. Subjects can be ranked based on the OPUS responses to UEFS module and responses to the TAPES as follows: Subject 2 and subject 3 joint first, then subject 4 followed by subject 1.

#### *5.5.1.2. SHAP*

As mentioned earlier in the thesis, the SHAP functionality index is calculated based on the time required to complete a set of tasks. Before commencing SHAP subjects are instructed to perform each task as fast as possible and as accurately as possible. Their performance is therefore a trade-off between speed and accuracy, based on the subject's own weighting.

None of the subjects reported substantial difficulty in performing SHAP tasks using the prosthesis although the SHAP functionality indices for all 4 subjects were notably low when they performed with their prosthesis compared to their anatomical arm performance. In line with this, as will be shown below time to complete the manual task in session 2 was also longer when using the prosthesis.

When the anatomical arm is used, it is expected to obtain a functionality index above 95 if the dominant side is used (233). Although the performance with the dominant side is generally faster than with the non-dominant side, an earlier study did not show significant difference between the overall SHAP functionality index between the two sides (234). This agrees with the findings in Chapter 4, where no clear differences were observed between the SHAP functionality index of the only left handed subject and other right handed subjects in V1.

Both subjects 1 and 4 showed functionality indices notably below normal range using their anatomical arm. However, it should be noted that normal SHAP functionality range has been established on adults aged between 18-25 years (25). It is known that functional abilities deteriorate with age (235). Metcalf et al showed that SHAP functionality index declines significantly from normal over the age of 65 year (233), which may help to explain this difference.

No comprehensive data set has been published on the functionality index range expected for upper limb amputees. However, studies that have measured SHAP in amputee subjects report scores ranging from 17 to 80 (114, 117, 118). The highest SHAP functionality index scored in this study was 63 (subject 3) and in Chapter 4, the mean SHAP functionality index at SHAP5 (completed before V4) was 67. This finding was surprising; given the vast difference in experience with using a prosthesis between the two groups and suggests some limitations with using healthy subjects and a prosthesis simulator to investigate prosthetic reaching. Two possible explanations for the findings are as follows. First, the existence of the anatomical arm that may have provided additional proprioceptive feedback to the subjects who participated in the study reported in Chapter 4. Second, the anatomically intact subjects had more opportunities to practice SHAP and hence there was a familiarity effect.

When considering the results of both the anatomical and prosthetic arm, it can be observed that the amputees who had a higher functionality index and shorter task completion time using their prosthesis (subjects 2 and 3) also obtained a higher functionality index and shorter task completion time when using their anatomical arm. This finding might be explained by the effects of age (233).

Nevertheless, if SHAP functionality indices are considered for the prosthesis only, the descending ranking of the amputees is subject 3, subject 2, subject 4 and then subject 1. This is similar to the rank suggested from OPUS and TAPES data, with subjects 2 and 3 performing best, followed by subjects 1 and 4.

### *5.5.2. Movement kinematics of session 2*

The four amputees stated that they do not normally perform the carton pouring task using their prosthesis. This is unsurprising, as it is a unilateral task that could be performed more conveniently using the anatomically intact arm (104). However, the subjects demonstrated the capacity to complete this task, both as part of the SHAP test (session 1) and in the laboratory (session 2) and did not show clear within-session learning effects in session 2 (see Figure 5. 7), as was seen in anatomically intact subjects, particularly in V2 (see Figure 4. 10).

#### *5.5.2.1. Movement duration*

As Figure 5. 6 shows, when using their anatomical arm, all subjects showed similar phase duration across all trials, particularly for reaching phase. All subjects took longer to reach when using their prosthesis. This is consistent with the findings of Chapter 4 where reaching in V1 took shorter than in V4 (Figure 5. 6).

In comparison to the results in Chapter 4, subjects in the present study showed a comparable group mean reaching and manipulation duration for the anatomical arm use to what was observed in V1 (1.1 s for reaching and 8.2 for manipulation 9.1 s at V1, and 0.98 s for reaching and 8.3 s for manipulation in the present study). Interestingly, similar phase duration is observable between the two groups when the prosthesis was used (3.1 s for reaching and 9.5 s for manipulation at in V4, and 2.8 s for reaching and 10.5 s for manipulation in the present study). Nevertheless, in particular contrast to the results in Chapter 4, no decrement in task duration over trials was observed in the present study (Figure 5. 7), even in the data of subject 2 who was not allowed to use the wrist rotator which he reported usually using.

Subjects 1 and 4 took about double the time in reach that subjects 2 and 3 needed. Difficulty associated with reaching is also shown in variation in phase duration within trials. This is supported by the data presented in Figure 5. 7; both subjects 1 and 4 were less consistent in their reach duration across trials compared to subjects 2 and 3. This suggests that both time to complete the reaching phase and between trials variation in phase duration seem to differentiate between subject’s skills.

Additionally, mean reaching phase duration and variability seem to reflect the subjects' ranking based on clinical evaluation tools; subjects with the highest ranks on all clinical tools (subject 2 and 3) showed a highly consistent phase duration across trials (Figure 5. 26 and Figure 5. 27). Subjects 1 and 4 who ranked the lowest according to their SHAP functionality indices and OPUS and TAPES responses also showed the longest and highest degree of variability in timing.

In the manipulation phase, subjects showed in general relatively similar mean durations (Figure 5. 6). However, Subject 1 in particular, who had the longest manipulation phase duration (1.41 s longer than Subject 4), demonstrated a high variance in timing across trials (Figure 5. 7). Once again, a similar general correlation with the clinical evaluation tools was shown; both subjects 2 and 3 showed the shortest manipulation duration compared to subjects 1 and 4 (Figure 5. 26 and Figure 5. 27).

#### *5.5.2.2. Joint angle*

In this work, effort was made to reproduce a similar experimental setup for all subjects; similar hand start point/endpoint and carton position on the table were used, also the distance between the carton and glass was fixed. Therefore, it was expected to observe consistent joint angle profiles across subjects; at least in the reaching phase (which is relatively constrained by the task requirement) regardless of the used hand. However, this was not clearly shown from the joint angle profiles (Figure 5. 8 and Figure 5. 9) which resulted in differences in the ROMs between-subjects (Figure 5. 10). However, this is probably because the movement in reaching phase is influenced by the subsequent movement in the manipulation phase (47, 236) in which movement would likely vary between subjects. For instance, subjects may hold the carton at a different height from the glass while pouring, or may choose to move the carton vertically during pouring. In addition, the position on the carton at which they acquire it may affect ROM in the reaching phase and subsequently in the manipulation phase. Such unavoidable between-subject variations in the performance have been suggested to affect the joint angle trajectories in earlier work (237). Large between-subjects variation in joint angles can be observed even in a more constrained manual task such as "turning a page" (238). Additionally, although using a prosthesis would impose restrictions on arm motion, different prostheses may restrict the ROM differently. This possibly depends on many factors; such as the shape and height of the proximal end of the socket, how snugly it fits around the elbow joint, and availability of wrist joint motion. Therefore, generally, the joint angle differences between-subjects may not reflect variation in the functional ability of the subjects.

It is interesting to observe notable differences in the joint profiles of subject 3 compared with other subjects while using the prosthesis during the manipulation phase. All subjects who did not use a wrist rotator (subjects 1, 2, 4) needed more shoulder abduction to pour the water using the prosthesis during the manipulation phase. This is consistent with the findings of Chapter 4 (compare ROM results in Figure 5. 11). Using the wrist rotator appeared to help subject 3 to complete the manipulation phase with minimal shoulder abduction as shown in Figure 5. 11. The shoulder adduction-abduction ROM was about $16^0$ in subject 3, compared to an average of $58.5^0$ in other subjects who did not use a wrist rotator.

#### *5.5.2.3. Movement variability*

*Temporal variability*

In the reaching phase, when the anatomical arm was used, all subjects exhibited low temporal variability (Figure 5. 14-A), consistent with the range observed in the study reported at V1 in Chapter 4. Phase duration variation shown in Figure 5. 7-A is also consistent with this observation. When the prosthesis was used, and as expected, higher temporal variability was consistently observed for all four subjects in comparison to the variability reported for their anatomical arm.

In comparison to the temporal variability reported in Chapter 4 during reaching phase, on average, the amputees showed slightly lower variability when using the anatomical arm (group mean warping cost for amputees = 4 whereas, 8 in V1) as well as while using their prosthesis (group mean warping cost for amputees = 21.4 whereas, 27.6 in V4). However, temporal variability differed considerably between subjects and it is also worth noting that none of the subjects showed temporal variability as high as the group mean value seen in V2 (see Figure 5. 14-A).

When the prosthesis was used, subjects 1 and 4 exhibited higher temporal variability (41.7 and 26.6 respectively) compared to subjects 2 and 3 (about 8.6 for both subjects) during the reaching phase. This is consistent with the large inter-trial variations in reaching duration shown in Figure 5. 7-B.

Temporal variability in reaching agreed with the general rank of the subjects according to the clinical evaluation tools; temporal variability metric suggests that both subject 2 and 3 achieved better performance than subjects 1 and 4 (see Figure 5. 26 and Figure 5. 27).

In regard to the temporal variability in the manipulation phase, although in Chapter 4 the anatomical hand had (V1) on average lower temporal variability than in (V4), between subjects variations were high for both sessions (see SD in Figure 4. 16, Chapter 4). This pattern was not seen in the study reported here. Subjects varied with some showing higher manipulation phase temporal variability with their prosthesis compared to their anatomical hand and others showing lower variability (Figure 5. 14-B).

In regard to the between-subjects variations in the manipulation phase, subjects 1 and 4 using their anatomical arm showed higher variability in phase duration (see Figure 5. 7-C) compared with subjects 2 and 3 who once again demonstrated similar temporal variability, as seen in Figure 5. 14-B. A somewhat similar pattern of temporal variability across subjects was seen when the prosthesis was used (Figure 5. 14-B); but with one notable exception. Subject 3 showed almost as high variability (warping cost of 86) as subject 1 (warping cost of 81). High temporal variability in subject 3 may be explained partly by her particular style of use of a wrist rotator during the manipulation phase. From the (gaze) video data, it was observed that the wrist rotator was intermittently operated, which caused variation in wrist rotation timing between trials thus increased the time warping cost.

Ranking subjects based on temporal variability perhaps is not applicable here; since one of the subjects used a wrist rotator during the manipulation phase. However, for illustration purposes, the subjects were ranked based on their temporal variability and then correlations with their ranking obtained from the clinical evaluation tools were derived (see Figure 5. 26 and Figure 5. 27).

*Magnitude variability*

Generally, during the reaching phase (Figure 5. 14-C), subjects showed similar variability in the acceleration magnitude for both arms, apart from subject 4 for whom variability using the prosthesis was greater. No clear explanation for this was found. In Chapter 4, the difference between V1 and V4 in magnitude variability was not clearly evident either.

In the manipulation phase, although magnitude variability resulting from the anatomical arm use was found to be consistently lower than what it is from prosthetic arm use (at least in three subjects (subjects 1, 3, 4)), the finding of Chapter 4 does not agree with this trend. In fact, magnitude variability was in average higher while using the anatomical arm in V1 compared to V4. In addition, subjects' ranking based on their magnitude variability in reaching as well as in manipulation phase, does not appear to agree with ranking based on the clinical evaluation tools.

In the manipulation phase, the high magnitude of variability observed in subject 3 is quite notable (Figure 5. 14-D). Subject 3 relied on the wrist rotator, rather than gradual shoulder abduction to tilt the carton for pouring during the manipulation phase. Visual inspection of the video data revealed that in order to use the wrist rotator for pouring, subject 3 translated the carton close to the glass by elbow flexion and external rotation (see joint profiles in Figure 5. 10) in a relatively consistent manner (see similar acceleration values in the first 3 s in Figure 5. 30-Subject 3). The wrist was then rotated, while stabilising the flexed upper arm against her body, with an associated gradual, but varied degree of shoulder internal rotation that may have changed the orientation of the forearm cluster. The variation in shoulder rotation between trials in this subject may be due to different degree and/or timing of wrist rotation achieved from a trial to another. In Figure 5. 30, examples of the forearm acceleration of all subjects during manipulation phase are illustrated. The raw data help to illustrate the higher temporal and magnitude variability in acceleration between-trials that have been observed for subject 3 during this phase in particular comparing to other subjects.

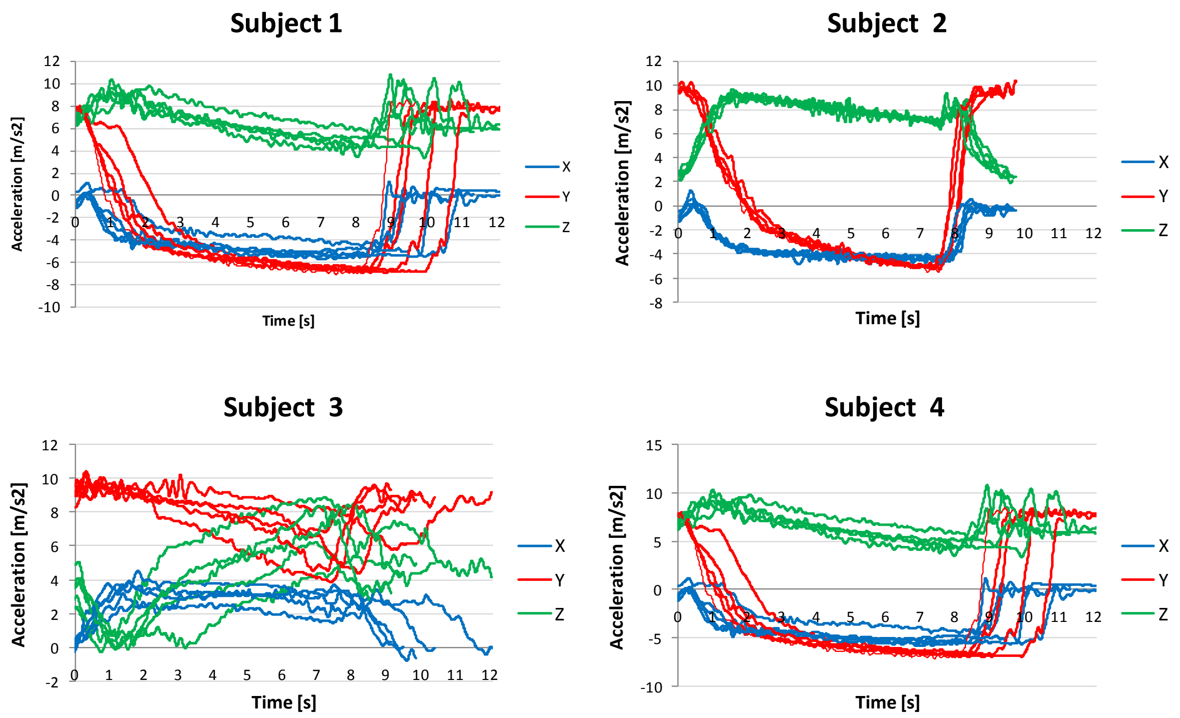



Figure 5. 30: Examples of 3D acceleration for all subjects during manipulation phase.

The magnitude variability is one of the few variables that did not show any significant change; neither between V1 and V2 nor between V2 and V4 in Chapter 4. Therefore, its correlation with data from the clinical evaluation tools are not presented.

Since Subject 3 used a wrist rotator to tilt the carton for pouring water during the manipulation phase, this influenced both the kinematics and gaze measures. Therefore, ranking the subjects based on their performance during manipulation phase should be considered with caution. The effect of introducing the wrist rotator was found to have somewhat contradictory effects. Although joint angles became closer to normal, movement variability increased. More importantly, gaze behaviour analysis showed disruption to the visual routine and a relatively high level of visual attention to the carton while pouring.

#### *5.5.2.4. Movement velocity and hand aperture during reaching phase*

Using the anatomical arm all subjects showed typical bell-shaped velocity and hand aperture profiles, similar to what Jeannerod found in his original work (27). A consistent time to peak aperture with mean of 0.59 s (about 60% of the reaching phase) was observed, which is highly consistent with the findings at V1 in Chapter 4 and comparable to what has been reported in the literature (32). Compared to the anatomical arm, reaching with the prosthetic arm was always slower and peak velocity took place later (see Figure 5. 15 and Figure 5. 16). Despite the differences in prosthetic hands (in terms of type and size) between subjects, all 4 amputees showed hand aperture profile with a distinct plateau as illustrated in Figure 5. 15.

In comparison to V4 in Chapter 4, anatomically intact subjects in the study reported in Chapter 4 showed similar group mean time to peak aperture (1.38 s) to the group mean of the amputee (1.37 s). Also similar aperture profile curvature with distinct plateau was observed in the two groups. This hand aperture plateau was also found in earlier works that have investigated kinematic characteristics of myoelectric (8) and body powered prosthesis use (5). However, peak wrist velocity was constantly higher in all amputees than in anatomically intact subjects (Figure 5. 16); yet still far from normal.

Hand aperture characteristics varied across subjects in this chapter. Time to peak aperture was only quantified in this chapter. Assumingly, the longer the time to peak aperture the poorer the performance; since more decoupling between the reaching movement and hand preshaping is encountered. Interestingly, time to peak aperture seems to be broadly in line with the clinical evaluation tools of users; subjects 2 and 3 showed much smaller time to peak aperture whereas subject 1 and 4 showed comparably higher time to peak. Amputees who demonstrated better functionality also exhibited a shorter time to peak aperture.

Nevertheless, certainly, subject 4's performance was affected partly by the slow finger movement of his hand (see slope of hand aperture profiles in Figure 5. 15). The extended time to peak aperture in subject 1 was mainly due to a delay in initiation of hand opening, rather than hand speed.

From Figure 5. 15, it can be also seen that subjects varied in the duration of the peak plateau. This might relate to some extent to prosthetic functionality. Bouwsema et al (8) for instance, reported a shorter aperture plateau duration in functionally superior myoelectric trans-radial prosthesis users to hybrid trans-humeral users but the difference was not found to be statistically significant. The existence of an aperture plateau may be inevitable regardless of functionality level, due to the mechanical properties of prosthetic hands.

Additionally, velocity characteristics varied between subjects, Figure 5. 16-B illustrates that subject 3 reached the highest average peak velocity, which helps to explain the short reaching phase duration (almost half the time that subject 1 and 4 needed). In turn, subject 2 who completed the reaching phase using his prosthesis in a comparable duration to subject 3, showed the lowest peak velocity (see Figure 5. 16-A). However from the velocity profiles in (Figure 5. 15), it is clear that when subjects 2 and 3 used their prosthesis, they had smoother velocity profiles with closer to normal bell-shaped curvature compared to subjects 1 and 4 whose velocity varied considerably over the reach. This may help to explain why subjects 2 and 3 were observed to complete reaching quicker. Although subjects' ranking based on the peak velocity does not fall in a line with the ranking of the clinical evaluation tools (Figure 5. 27 and Figure 5. 28), from observation it appears that the smoothness of the velocity profile would agree with the clinical evaluation tools.

### *5.5.3. Gaze data of session 2*

As in Chapter 4, the discussion will focus on the extent to which gaze behaviour follows a repeatable and efficient pattern, as shown from number of transitions between AOIs to complete the task. This will then be followed by a discussion of the duration spent at each AOI between anatomical and prosthetic arm use, and between subjects when the prosthesis is used. Then the focus will be only on those AOIs that showed major differences in gaze duration between anatomical and prosthetic arm. Based on these comparisons and building on what was found in Chapter 4, subjects are ranked based on their gaze duration profile. Finally, gaze duration using aggregated AOIs during reaching will be discussed. Note that gaze data from subject 3 was limited, particularly in the reaching phase and hence the discussion below should be read with this in mind.

#### *5.5.3.1. Reaching phase*

In the reaching phase, the average number of transitions observed varied both between subjects and between conditions (anatomical arm use vs. prosthetic arm use). In general, contrary to the findings in Chapter 4, 3 subjects exhibited fewer transitions when the prosthesis was used compared to their anatomical arm use during the reaching phase. This was the case for subjects 2, 3, and 4. This unexpected difference between the anatomical and prosthetic arm can be explained by considering the gaze fixation duration at AOIs that is discussed below. Comparing to V4 in Chapter 4, these 3 subjects also showed fewer transitions during reaching with their prosthesis.

Subjects 2 and 3, in particular, made fewer transitions when using their prosthesis compared to performance by subjects 1 and 4 with their prosthesis, it can be assumed, therefore, that subjects 2 and 3 have more stable gaze pattern than subjects 1 and 4 (Figure 5. 20-A). The stable gaze patterns exhibited by subjects 2 and 3 can also be seen from the gaze sequences presented in Figure 5. 18. Given that subjects 2 and 3 were the two subjects whose ranking based on clinical evaluation tools and kinematic variables was the highest, this observation may be consistent with the hypothesis that skilled upper limb task performance is associated with a typically stable gaze routine (Figure 5. 28 and Figure 5. 29). Stable patterns of gaze behaviour have been reported in experts in sports (185, 239) as well as in studies of tool use (68). This is further supported by other gaze behaviour aspects discussed below.

Although subjects varied in their gaze behaviour when the anatomical arm was used (see Figure 5. 21, and Figure 5. 24), a broad agreement with the findings of Chapter 4 can be observed. Figure 5. 23 indicates that during the reaching phase, using the anatomical arm involved mainly fixation at AOIs related to the top of the carton (including "Above GCA", "Above Carton", and "Spout"), and less frequently AOIs related to the GCA. Using the prosthesis, periods of fixation at "Hand" and "Following hand" AOIs were observed. Additionally fixation at GCA became dominant.

As Figure 5. 21 shows, when subject 2 and 3 used their prosthesis, the gaze fixation was mainly and consistently at GCA during the reaching phase (i.e. in subject 2 gaze fixation at GCA was about 96% of gaze fixation in reaching). Subjects 1 and 4 in addition to fixations at the GCA were also found to fixate at their prosthetic hand and to follow their hand. In Chapter 4, it was concluded that fixation at "Hand" and "Following hand", in particular, is associated with uncertainty of the hand position/status which precludes planning ahead for grasping thus increased the attentional demands of the reaching phase.

From the aggregated AOIs in Figure 5. 24, it can be observed that subject 3 did not make any fixation at "Hand related" AOI and fixated 55% at GCA related AOIs (note 43% of the data was lost), and subject 2 only fixated at hand related AOIs for 1% of the gaze fixation in the reaching phase and almost 96% at "GCA related AOIs". In turn, subject 1 showed fixation at "Hand related" AOI for about 34% and 47% at "GCA related" AOIs and subject 4 fixated at "Hand related" for 7% and 77% at "GCA related" AOIs. These observations provide supportive indication for the findings in Chapter 4; where better prosthetic performance was associated with less fixation at "Hand related" AOIs and increase in gaze duration at GCA related AOIs. The difference between-subjects at "Hand related" AOIs in particular reflects the general ranking of the subjects based on clinical evaluation tools (Figure 5. 28 and Figure 5. 29).

As discussed in Chapter 4, fixation at “GCA related” AOI at the beginning of reaching may indicate planning for grasping, but later on in the reaching phase when the hand is in the vicinity of the carton it is likely to relate to the need for visual feedback to guide the grasping. In broad terms, stable gaze fixation at “GCA related” AOI in subject 2 and 3 suggests an increased ability to plan ahead of grasping compared to subjects 1 and 2. However, grasping seems to be demanding to the extent it requires visual feedback even from expert users.

In conclusion, the gaze transition pattern, gaze sequence and gaze fixation duration together provide evidence of development of an efficient visual routine in subjects 2 and 3 during the reaching phase which is in line with the findings of the clinical evaluation tools (Figure 5. 28 and Figure 5. 29) and kinematic measures. This routine, nevertheless, suggests close attention to the grasping action. Therefore, it does not resemble the gaze routine seen in reaching with an anatomical arm in which the main concern is on the forthcoming manipulation phase as indicated by fixation at AOIs located at the top of the carton and fixations at “Glass” and “Above Glass” AOIs, sometimes seen even before the grasp was established.

#### *5.5.3.2. Manipulation phase*

As discussed in Chapter 4, the manipulation phase comprises a number of sub-actions, making its analysis quite difficult. Unlike the reaching phase, the number of transitions was greater when the prosthesis was used than when performing with their anatomical arm in all subjects (Figure 5. 20-B). In comparison to V4, in which on average 12 transitions were made by the subjects during the manipulation phase, a similar number of transitions were made on average by the amputees while using their prosthesis (about 13 transitions), however, unlike in V4, high variations were observed between-subjects. Subject 2 showed the lowest number of transitions (around 9), followed by subject 1 and 4, this rank does not agree well with the ranking obtained from clinical evaluation tools. Interestingly subject 3 for whom functionality was the best, showed far more transitions than others (around 20 transitions). When her data was inspected, this subject was found to make many transitions between AGL/PCA and Spout/AGC while tilting the carton for pouring action. This may be linked to wrist rotator use. No doubt tilting the carton using the wrist rotator enhanced the aesthetic appearance of the movement. However, unlike using the anatomical shoulder joint, the wrist rotator does not provide proprioceptive feedback about the orientation of the carton in space. Therefore, vision became the only available source with which to obtain information about the orientation of the carton during pouring. As a result of wrist unit use in subjects 3, ranking based on number of transitions in manipulation phase did not follow the general ranking of clinical tests (Figure 5. 28 and Figure 5. 29).

In general, when the anatomical arm was used, a similar gaze fixation distribution was observed to that seen in Chapter 4 (V1) (see Figure 5. 23). Gaze fixation was mainly at PCA/GL due to the task demands. This is also associated with short fixation durations at AGL, AGC mainly in the first of first half the manipulation phase (see gaze sequence in Figure 5. 19). At a late stage in manipulation phase, some short fixations occur at BGC and CEP which are probably related to planning for carton placement on the table (see gaze sequence in Figure 5. 19). Consistent with the findings in Chapter 4, no fixation at GCA took place during manipulation when the anatomical arm was used (Figure 5. 23).

Different gaze fixation distributions were seen for different subjects when the prosthesis was used. However, all amputees regardless of their functionality level, and in line with V4, showed fixation at GCA. Fixation at GCA was less than 10% in all cases, nevertheless, as it took place consistently at the beginning and end of the manipulation phase in all subjects (see gaze sequence in Figure 5. 19), it suggests that it plays a specific functional role. As discussed in Chapter 4, gaze fixation at GCA in the manipulation phase can be seen as uncertainty about the hand's status, due to an absence of feedback from the hand. In the early stage of the manipulation phase, attention to the GCA may be needed to ensure a secure hand grip has been achieved in the early stages of lifting the carton. At the end of the manipulation phase, when releasing the carton, visual information on hand aperture is needed to ensure the aperture is larger than the carton width before withdrawing the arm. Gaze fixation at GCA while transferring/ pouring from the carton also occurred on 3 occasions in subject 1 and once in subject 2.

In line with gaze behaviour observed in Chapter 4, gaze fixation at AGL was frequently observed when the anatomical arm was used in all subjects, see Figure 5. 19 and Figure 5. 22, (although in subject 3, the gaze data was very limited during the relevant part of the manipulation phase). This behaviour, which could be interpreted as planning for the pouring task was also observed in all subjects when the prosthesis was used, apart from subject 1 who showed the lowest level of functionality. Planning to return the carton to the table (by fixating at CEP and BGCA) however was maintained when either arm was used in all subjects.

Generally, the differences in gaze behaviour during the manipulation phase between prosthetic and anatomical conditions and between subjects were less obvious than those seen in the reaching phase and mainly took place in the beginning and end of manipulation phase. This, as discussed in Chapter 4, is probably due to the challenging nature of the chosen manual task in which careless performance might lead to water spillage. However, the observed differences suggest visual attention at the hand-carton interface (GCA) which was never seen in anatomical arm use.

### 5.6. Conclusion

In this chapter, both OPUS and TAPES were not able to differentiate between subjects 2 and 3. Although some questions in the questionnaires touch on the general aspect of difficulty of task performance (e.g. asking about the difficulty associated with performing ADLs using the prosthesis), the inevitable subjectivity of questionnaires may well bias the results. More importantly, the results from the questionnaires cannot indicate which aspects to focus on to improve performance. Indeed, it is possible to argue that SHAP also provides limited useful information in this regard. However, the time measure appears to be indicative of learning (as demonstrated in Chapter 4) and sensitive enough to differentiate between subjects with close functional ability (as demonstrated in the present chapter).

In Chapter 4, although functionality (as measured by SHAP), in addition to many temporal kinematic characteristics of variables, improved over practice, the difference between anatomical and prosthetic performance remained evident. The study presented in this chapter further underpins this finding. All subjects in this study were established users who are supposedly skilled in using their device. Logically, although subjects may retain different levels of skill, it is not unreasonable to assume that the kinematic differences partly reflect anatomical arm/prosthesis differences.

Although the prosthetic performance revealed distinct kinematic differences between-subjects, the within-subject differences (between the anatomical and prosthetic arm) were also consistently evident in all subjects for certain kinematic variables. In reaching, the anatomical arm was always faster. Subjects also showed a more consistent timing within session (mainly in reaching), which was further supported by the temporal variability results. Anatomical arm movement additionally was smoother and highly stereotypical in reaching. The kinematic differences between anatomical and prosthetic arm in manipulation phase were not as clear as in the reaching phase. However, the manipulation duration was always shorter when using the anatomical arm.

Despite the fact that all 4 subjects had significant experience with using their myoelectric prosthesis, amputees still showed kinematic characteristics while reaching to grasp using the prosthetic hand that were similar to those observed in grabber users after a short period of practice (67) and also in deafferented subjects (33, 42). Reaching to grasp, from studies in each of the three groups is characterised by longer movement time and lower time to peak velocity compared to their contralateral intact arm/ control subjects. Further, in each of the three groups, reaching velocity does not show a smooth single-peaked profile (as seen in anatomical hand reaching) and the hand aperture profile is characterised by a prominent plateau.

Furthermore, unlike the anatomical arm performance that showed attention to the overall task requirements, and despite the considerable experience with prosthetic use, gaze behaviours indicated a high level of attentional demands to the immediate task (i.e. guiding the prosthesis and monitoring the grasp). This shown by the long gaze fixation at the hand/carton interface area (GCA) in all subjects, and fixation at the prosthetic hand (that was also seen in V4 Chapter 4) in some subjects. This gaze behaviour largely precluded planning ahead actions, particularly during reach and grasp (reaching phase). This distinct difference was mainly evident in the reaching phase.

Generally, the distinct differences between the anatomical and prosthetic arm validate the earlier investigation in Chapter 4. Kinematic and gaze behaviour differences between performance with each arm reported in this Chapter were generally similar to the differences in behaviours between V1 and V4 in Chapter 4. Also kinematic and gaze behaviours when using the prosthetic arm in this chapter were similar to behaviours seen in V4 in Chapter 4. This is despite the age difference between the two groups and massive difference in practice using the prosthesis.

Only two of the skill measures showed a perfect correlation with the ranking of one of the clinical evaluation tools (SHAP), namely the temporal variability in reaching phase (Figure 5. 26) and gaze duration at Hand-related AOIs (Figure 5. 27). However, given the marginal differences in most outcome measures between subjects 1 and 4, and subjects 2 and 3, perhaps it is sensible to consider the subjects in two groups: “skilled” users (subjects 2 and 3) and “less skilled” subjects (subjects 1 and 4). When subjects are clustered like this, both OPUS and TAPES rankings agreed with the ranking according to SHAP. Additionally, many of the measures of skill also agree with the clinical evaluation tools, see Figure 5. 26-Figure 5. 29. In summary, reaching duration, manipulation duration, time to peak aperture, temporal variability in reaching, number of fixation transitions in reaching and gaze duration at Hand related AOIs all indicated the superiority of subjects 2 and 3 over subjects 1 and 4. This reinforces the conclusion that kinematic and gaze behaviours may reveal the underlying control processes that lead to activity and functional restrictions in everyday life (as reflected in the clinical evaluation tools).

Finally, the tools to characterise kinematic and gaze behaviours may be useful in establishing the “quality” of the performance; and maybe providing an indication of whether or not amputees would use their prosthesis in daily life. For example, if the performance of tasks with a prosthesis is attentionally demanding, then it is debatable whether it will be well used in a free-living situation, regardless of how fast and accurate the subject’s performance is in a lab situation.

Probably the main limitation of this study is the very small sample size which prevents any generalisation. This is mainly due to the limited number of active myoelectric prosthesis users in the region. Also, despite the dramatic improvement in eye tracking technology over recent years, not all eyes are easily trackable. Subject 3, had eyes that are not easily tracked. Although eye tracking calibration was successful, the eye location was lost very frequently. Therefore, interpretation of the data of this subject in particular should be considered with caution.

# Chapter 6: Discussion and conclusions

## 6.1. Introduction

The myoelectric prosthesis is designed to restore the cosmetic and functional loss of upper limb amputees. However, although current systems offer a high degree of cosmetic restoration, the extent to which they restore function remains limited (3). The limited function offered by current devices may well be part of the reason for the consistently reported poor usage levels and high rejection rates (3).

Despite considerable effort in the development of new prostheses and EMG control approaches; there has been remarkably little work to understand the precise mechanisms underlying the poor functionality. In particular, despite repeated mentions in the literature of the reliance of amputees on vision to control their prosthesis, with one notable exception (the ongoing and closely related work at the University of Groningen, Groningen, The Netherlands (117, 240)), this is believed to be the first thesis to investigate in detail the visuomotor behaviours associated with myoelectric prosthesis use. Note, the author and his supervision team were in discussion with the Groningen group from 2009 onwards and the two studies have evolved in parallel.

The main findings of the thesis are discussed below.

Following a brief introductory chapter**, Chapter 2** established the rationale for the thesis. The chapter began with a brief introduction to upper limb functional anatomy, with a particular focus on the hand. This led to a review on motor control of the anatomical hand in reaching to grasp and in multi-stage manual tasks. The review showed that upper limb movement is planned using internal models for the movement which are learnt with practice (27, 28, 30, 31). The review highlighted the stereotypical kinematic characteristics seen in reach to grasp (27, 28, 30, 31) and the roles of vision and proprioception in movement control (1, 33). The similarities between a prosthetic hand and a hand-held mechanical gripper were noted, followed by a brief review of characteristic kinematics when using a hand gripper to perform a reach to grasp. Interestingly humans can also learn to extend the internal kinematic models to incorporate the movement of handheld tools and thus use them as an extension for the arm (55, 241). However, even following extensive practice, tool use kinematics suggests a greater reliance on vision to control the reach to grasp movement (64, 66).

The following part of this chapter introduced the reader to the literature on amputees and myoelectric prostheses. As a natural starting point, an introduction to amputation, its levels, incidence and prevalence and alternative types of upper limb prostheses were presented to the reader. This was followed by a section describing the technical aspects of myoelectric prostheses including control strategies, components, and perceived limitations. Current approaches for evaluation of upper limb prosthesis wear, usage and functionality were presented, with a particular focus on the clinical evaluation tools for adults (OPUS and TAPES questionnaires and SHAP and ACMC clinical tests). The high rate of prosthesis rejection/abandonment and factors that lead to rejection/abandonment were then highlighted. It was concluded that current myoelectric prostheses offer a poor degree of functional restoration and that although current clinical evaluation tools serve to highlight the extent of the problem, they provide little or no insight into how to improve the design of prostheses, or of training programmes.

The small number of papers in motor control and motor control learning in trans-radial prosthesis users were then discussed. Studies of trans-radial amputees performing pointing tasks highlighted the relatively small impact of amputation and prosthesis properties on planning and execution of goal-directed pointing tasks (7, 133). Secondly, kinematic characteristics of the reaching to grasp with a prosthesis were addressed. Generally, studies reported clear deviations from the motor control strategy seen in anatomically intact reaching to grasp (5, 8). In particular, these studies found that velocity profile of reaching movement is characterised by a short acceleration phase and long deceleration phase. The prosthetic hand also starts to close near to the end of the reach to grasp trajectory, resulting in a noticeable plateau in hand aperture profile. This showed similarities with the movement patterns seen in reaching to grasp using a mechanical gripper and supported the hypothesis that amputees are more reliant than anatomically intact subjects on visual feedback to control reach to grasp.

Following on from this, studies of learning to use a myoelectric prosthesis were reviewed. It was clear that certain aspects of performance with a prosthesis improved with practice (133, 136-138, 151, 152). For instance, with practice, both reaction time and movement time were found to decrease during the performance of functional tasks (136-138), also smoother EMG signals were observed after learning to open and close myoelectric hands (152). Nevertheless, the literature was limited in its breadth, both in terms of the tasks studied and the reported parameters. For example, studies reported kinematic characteristics in simple goal directed pointing tasks (133), and the accuracy and speed of achieving desired hand apertures in reach to grasp tasks (151-153). Studies that involved subjects performing ADLs relied heavily on time-based indices (such as task duration and reaction time) to describe the performance (136-138). Such studies arguably provide limited additional insight over what can be gained from the use of clinical tools, such as SHAP. Surprisingly, at the start of this PhD, to the researcher's knowledge there were no published reports on gaze behaviour during upper limb prosthesis use.

**Chapter 3** had two aims; to identify a manual task to be used in the studies reported in subsequent chapters and to establish a coding scheme with which to analyse the gaze data. A number of requirements were first identified, that took in account the nature of the investigation and difficulty associated with prosthesis use. Based on these criteria an everyday manual task, pouring water from a carton into a glass, was chosen.

Some of the most famous studies of gaze behaviour in complex functional task performance have not reported an explicit and detailed coding scheme and have implicitly considered the objects in the scene to be the Areas of Interest (AOI) (48-51). However, this approach, while simple, may be prone to bias on the part of the coder. Further, a number of recent studies have shown that useful information can be gained from considering whereabouts on the object gaze is focused (38, 186-188). In the coding scheme that was developed, the visual scene was subdivided into a number of AOIs. A given AOI can be an object, a part of an object or an area associated with interaction between objects. The coding scheme accounts for the overlapping between two or more AOIs, by either introducing a new AOI, or prioritising one of the overlapping AOIs. The coding scheme was defined in detail and consisted of 14 AOIs.

To examine the suitability of the identified task and the suitability and reliability of the coding scheme, two independent raters coded gaze data gathered for two subjects under two testing conditions (using the anatomical arm and using the prosthesis to complete the task). The results indicated that under the two testing conditions, the task satisfied the requirements. These results suggested the suitability of both the task and the coding scheme for the subsequent investigations. Additionally, when comparing the coding results of two raters, a high level of agreement was observed in the total fixation duration at each AOI, under both testing conditions (see Figure 3. 10). Inter-rater reliability was further confirmed statistically. Based on these results, the identified task and the coding scheme were used in the subsequent investigations reported in Chapter 4 and Chapter 5.

**Chapter 4** addressed the lack of a comprehensive understanding of the behavioural changes associated with learning to use a myoelectric prosthesis. For this purpose, kinematic and gaze data were gathered in seven anatomically intact individuals using their left (anatomical) hand during performance of the manual task identified in Chapter 3. These data were used to establish a baseline against which to compare performance with the prosthesis. Additionally, anatomical hand functionality was recorded using a validated clinical test of hand function, SHAP. Following fitting of a myoelectric simulator, the same kinematic and gaze parameters were gathered in three testing sessions over a period of 2 weeks. Over the same period, scores on SHAP were also gathered on four separate occasions. It was proposed that those measures whose values reverted towards those seen at baseline may be considered to reflect skill acquisition.

The data were first segmented into reach and manipulation phases. The set of kinematic parameters calculated from the motion data included movement time, joint angle ROM, and temporal and spatial movement variability. Additionally, wrist velocity and hand aperture profile were calculated for the reaching phase only. The gaze data allowed calculation of gaze fixation sequence, gaze fixation duration at AOIs, and number of transitions between AOIs for the reaching and manipulation phases.

The SHAP results (see Table 4. 4) indicated a dramatic decline in hand functionality following introduction of the prosthesis, but these scores improved significantly with practice. Broadly, most of kinematic and gaze variables showed significant changes when the prosthesis was first introduced, most of which indicated a deterioration in performance (e.g. slower, more variable). The influence of practice on the values of the kinematic variables varied; while certain variables indicated significant improvement (including task duration and temporal variability during reaching and in the manipulation phase, and both time to peak aperture and peak velocity in the reaching phase), others showed no significant change.

Over the period of practice using the prosthesis, most gaze variables showed a general trend of mean values slowly reverting towards values seen at baseline, but the change was not significant in any of them. More importantly, during prosthesis use, it was seen that subjects often fixated at the hand or followed the hand during reaching phase as shown in Figure 4. 23. Further, they generally maintained their gaze at the hand/carton interface (GCA) until the carton was lifted (see gaze sequence in Appendix I). Interestingly, with practice fixation at the hand/ following hand decreased and gaze at GCA increased (see Figure 4. 23). These observations were generally indicative of increased visual attention on the immediate task (reaching and then grasping the object), which negatively influenced the ability to anticipate and plan for the subsequent (manipulation) phase; a fundamental feature of gaze behaviour in anatomically intact individuals performing a multistage task (54). For instance, in line with the previous studies (38, 49), when using the anatomical hand, gaze, during the later part of the reaching phase/very early part of the manipulation phase, often fixated at areas relevant to the forthcoming part of the task; in this case, at Glass/Above Glass, presumably anticipating the pouring action even before the carton left the table. When the prosthesis was used, and probably due to the need to visually inspect grip formation and monitor grip security, anticipatory behaviours were severely compromised.

Finally, the learning process reported in this chapter was assessed against Fitts and Posner's three-stage model of learning (222). It was noted that the behaviours seen at the end of the study suggested that subjects were likely to be in the middle stage of learning (associative stage).

**Chapter 5** had two primary aims. The first aim was to investigate whether the use of anatomically intact subjects to investigate visuomotor behaviours may be a useful model for future studies. The second aim was to investigate the relationships between the new measures of skill and established clinical measures of function and upper limb functional status and functional restriction.

For this purpose, an experimental protocol was developed and four unilateral trans-radial amputee users of myoelectric prostheses were recruited to the study. In the first session, each subject's performance using their own prosthesis was evaluated using SHAP and two standardised questionnaires (OPUS and TAPES). In addition, subjects' performance on SHAP using their intact hand was also evaluated. The three evaluation tools provided a comprehensive picture of each subject's functionality and perceived level of activity and functional restriction in everyday life. In the second session, visuomotor behaviours were investigated for both hands using the same methods as described in Chapter 4.

Although the small number of subjects greatly limited the ability to generalise the results to other populations, a number of observations could be made. Despite all four users having significant experience in using their prosthesis the results of the laboratory study of visuomotor behaviours were generally surprisingly similar to those found at the end of the protocol reported in Chapter 4 (V4). Two subjects (subjects 1 and 4) out of four showed similar performance with their prosthesis to the average performance of intact subjects at V4, while the other two subjects performed slightly better. Additionally, when using their intact hand, both SHAP results and visuomotor parameter values showed good agreement with the values seen at baseline in the study reported in Chapter 4. Gaze behaviour when using the prosthesis was of particular interest and all subjects, in agreement with the findings of Chapter 4, revealed a high reliance on visual feedback when reaching and particularly when grasping the carton (see Figure 5. 18 and Figure 5. 21). Again, there was seen to be a decrement in the ability of the amputee subjects (regardless their functional ability, or type of prosthetic hand) to plan for the manipulation phase.

Results of the questionnaires indicated that all 4 amputees reported regularly wearing their prosthesis in everyday life. Additionally, all amputees were able to complete SHAP when using their prosthesis, but with different timing and hence functionality indices (see Figure 5. 5). Interestingly, subjects who performed less well on SHAP and reported more difficulty with using their prosthesis (OPUS and TAPES) also tended to perform less well on the pouring water task. Furthermore, despite all subjects being experienced users of myoelectric prostheses and reporting frequent use of their prosthesis in everyday life, the visuomotor behaviours seen suggested none of the users had yet reached the autonomous stage of learning (based on Fitts and Posner's model (222)).

The existence of significant gaze fixations at the hand or pursuing the hand in the two poorer performing subjects during reaching to grasp with the prosthesis was notable. In the only other study of gaze behaviour in amputees, in 2011 Bouwsema et al (117) also observed in a study of established trans-radial prosthesis users that some users fixated their gaze at the prosthetic hand while reaching to grasp objects. Such a behaviour is almost never seen in reaching to grasp with the anatomical hand (242), and probably indicates uncertainty about the hand position or state. The results are consistent with gaze duration of the hand/pursuing the hand being negatively related with performance on clinical measures of function and functional status. A larger, longitudinal study would be needed to investigate whether tendency to fixate/pursue the hand declines with functional improvement in amputees.

### 6.2. Future work

To the author's knowledge, this thesis is the first to describe movement kinematics and gaze behaviour seen during the performance of a functionally relevant task when using the anatomically intact and a myoelectric prosthetic hand in both anatomically intact subjects and amputees. These preliminary findings have several implications for the development of prosthetic devices, and training approaches and the key issues are discussed below:

### *6.2.1. Insights into the design of prosthetic devices with artificial feedback*

The lack of direct feedback from the prosthesis has long been recognised as a major limitation of myoelectric prostheses (3). Several groups have reported on prototype systems that provide artificial sensory feedback to the residual limb on the myoelectric prosthesis state (162, 163, 243-246). These studies have investigated the effects of various methods of feedback of parameters including hand opening/closing status, finger contact state and grip force. Feedback methods have included stretching of the skin, and electrical stimulation,. To the author's knowledge, none of these biofeedback systems have been commercialised. One reason may be the lack of clear and detailed evidence on the benefit of introducing artificial sensory feedback. The work reported in this thesis provides a potentially sensitive tool with which to evaluate new prostheses with artificial sensory feedback. For example, in this thesis, it has not only been shown that visual feedback is heavily used to guide task performance, but also shown how and in what phase(s) of the task vision is used.

The results showed that less experienced/skilled users had to employ vision to guide prosthetic hand movement towards the object, but that more experienced/skilled users were able to reduce, or even eliminate this dependency on visual feedback in the early part of reach. The ability to accurately reach towards a target with no visual feedback on the prosthesis in expert trans-radial amputees has been interpreted as an indication of incorporating the prosthesis within the internal model of the upper limb (7). However, visual feedback is used to guide grasping and releasing objects which seemed to persist regardless of practice duration/ experience, or skill level (see gaze sequence in Figure 4. 20 and Figure 5. 17). Therefore, it is reasonable to suggest that amputees may benefit from feedback on for example object-hand grasp force, to allow them to move visual attention to subsequent parts of a given task. Specifically, if introducing artificial feedback could be shown to improve the ability of the user to use vision to plan subsequent phases of a multi-stage task, rather than focus on the immediate task, there would be good reason to assume it would be an improvement over existing systems.

### 6.2.2. *Assessment of training outcomes*

The results of this thesis suggest that visual behaviours when using a prosthesis to perform a functional task is distinctly different to those seen when performing the same task with the anatomical hand. However, in Chapter 4, certain gaze behaviours showed trends towards baseline over practice. The same measures of gaze behaviour also differentiate between prosthesis users in a manner that seems to be broadly consistent with their levels of proficiency in prosthesis use (as indicated by clinical evaluation tools).

In current approaches to training amputees to functionally use a myoelectric prosthesis, the amputee is taught how to perform the manual tasks using the prosthesis. However, there is no validated approach to measuring the effectiveness of the training, in terms of the user's skill level. The measures of skill that have been established in this thesis provide a promising tool with which to quantify skill in clinical settings. Although kinematic measures described in the thesis relied on an expensive motion analysis system, with a small amount of additional work (e.g. instrumenting the object to be acquired) most of the useful kinematic measures could be acquired using small, portable and relatively cheap sensors, such as accelerometers and goniometers. Further, eye tracking technology while expensive to purchase is now portable and relatively straightforward to setup, although time consuming to analyse.

### 6.2.3. *Gaze behaviour training*

Gaze behaviour has been used as way of monitoring skill acquisition in many domains (see review (206)), based on the observation that with training, gaze behaviour of the trainees more closely resembles the gaze behaviour of expert users. More interestingly, feedback on gaze behaviour might also be used as part of the training procedure itself (209, 247-249). This approach has been successfully demonstrated in training basketball players on free throw shooting (249). Following the same line, Sadasivan et al (209) suggested a feedforward training scheme for novice pilots in which novices are provided with the gaze scan path of an expert pilot to follow. The training approach was shown to lead to improved performance (209). Using the gaze sequence of expert users of a laparoscopic instrument with which to train novices was found to decrease movement time and the number of errors (247).

Previous studies that have suggested the benefit of gaze training for skill acquisition have been conducted in anatomically intact subjects (209, 247-249). The value of gaze training in subjects with sensory motor impairment, such as upper limb amputees, remains the subject of further work. In Chapter 5, in contrast to the less skilled amputees, the two more skilled subjects appeared to be capable of initiating reaching with virtually no overt attention to the prosthesis. This behaviour was interpreted as an indication of the subjects having adapted their internal arm model to incorporate the prosthesis. Additionally, following carton acquisition, the two more skilled amputees rarely paid attention to the GCA, suggesting confidence in the prosthetic grip and a reduced reliance on visual feedback to confirm its status. However, clearly, all 4 subjects showed some aspects of gaze behaviours with their prosthesis that differed markedly from those seen when using the anatomical hand (e.g. prosthetic use was associated with gaze fixations at the GCA for most of the reaching phase, whereas anatomical hand use showed fixations mainly at AOIs above the GCA, such as AGC and SP). Hence, attempting to train amputees to follow “normal” gaze behaviour may not be a sensible way forward, as the results suggest that certain characteristics of amputee reach-grasp gaze behaviour may be fundamental to the need to substitute for the missing proprioceptive information. Nevertheless, gaze training based on examples from skilled amputee subjects, is worth further investigation.

#### *6.2.4. Automating gaze coding and characterising gaze behaviour during performance of the SHAP test*

Inspired by the work discussed in this thesis, and the work of Bouwsema et al (117), a research team from the University of New Brunswick in Canada has begun further work on analysing gaze behaviour in amputees performing the complete SHAP test[‡‡‡]. The initial work of the New Brunswick research team is aimed at both removing the potential for coding bias and speeding up the analysis of gaze data, through the use of artificial vision techniques (250). The long term aim is to produce a comprehensive assessment tool of function and visuomotor behaviour.

### 6.3. Thesis limitations

#### *6.3.1. Numbers of subjects*

Perhaps the main limitation of this thesis is the small number of subjects in each of the two main studies. This suggests caution in generalising from some of the results, notably those in Chapter 5. However, it is worth mentioning that small sample sizes are typical of eye tracking studies (see recent review (206)), mainly because gaze data analysis remains very time consuming.

[‡‡‡] Personal communications with Dr. Peter Kyberd, University of New Brunswick, Fredericton, Canada.

### *6.3.2. Task segmentation*

The importance of task segmentation into primitive phases was recognised at an early stage of this thesis. Most previous studies that have investigated movement characteristics in a functional task for the anatomical and prosthetic hand, focussed on reaching to grasping tasks (27, 28, 30, 31, 44). Accordingly, it was sensible to identify this part of the task performance in order to compare results of this thesis with previous literature. Therefore, the task was divided into a reaching phase and a manipulation phase. However, with the current approach it is difficult to interpret the functional meaning of manipulation phase gaze fixation at a given AOI, as this may change over the phase. Therefore, future work should consider dividing the manipulation phase into a number of sub-phases. For instance, in the studied task, sub-phases such as carton transport, water pouring and carton release could be defined.

As many of the interesting results emerged from analysis of the reaching phase, it may also be of interest to segment the reaching phase into sub-phases. As discussed above, the reaching phase showed distinct visuomotor differences between skilled and less skilled amputees. For some of the variables studied, these differences were confined to a certain part of reaching phase. For instance, in contrast to the less skilled amputees, the two more skilled subjects carried out the initial hand movement towards the object with no visual feedback on the prosthesis. However, both groups had to pay high overt visual attention to the hand/carton interaction (GCA) during object acquisition later in the reaching phase. Therefore, there may be advantage to be gained in future studies from segmenting reaching phase into early and late reach sub-phases.

## 6.4. Novel work in the thesis

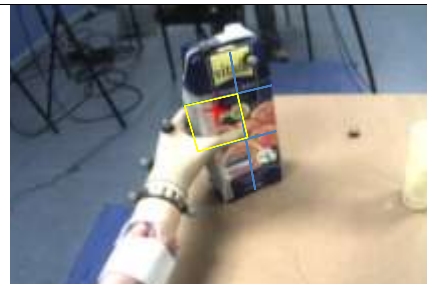
1. The development and validation of a novel coding scheme for a multi-stage upper limb functional task;

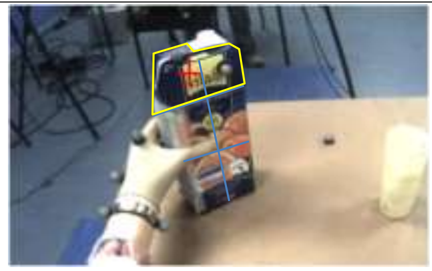
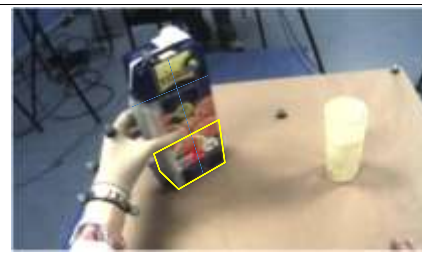
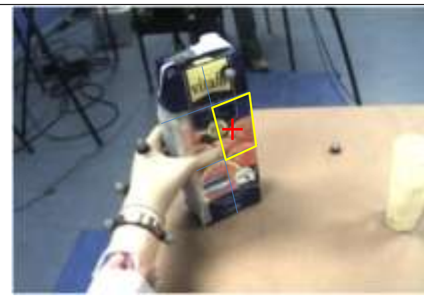
2. The first detailed report of visuomotor behaviour changes over training to use a myoelectric prosthesis simulator in a multi-stage upper limb functional task and hence identification of several measures reflective of skill acquisition. The study is also the first to report on the disruption to planning ahead behaviour when using a prosthesis, resulting from the need for visual feedback on the immediate task;

3. The first detailed demonstration of the potential validity of studying visuomotor behaviours in anatomically intact subjects who use a myoelectric prosthesis simulator as a method to investigate new prostheses or training approaches;

4. This was the first study to show evidence of a relationship between detailed visuomotor behaviours and self-report measures of functional restrictions, such as TAPES and UEFS of OPUS.

## Appendix A: The AOIs

| AOIs | Definition | Example |
|---|---|---|
| Hand | The area that the hand occupies (up to ulnar and radial styloids) in addition to the area confined between the thumb and the index finger |  |
| Following Hand | An AOI that exists when the point of regard is close to the boundary of the hand and moving with the hand. | N/A |
| Grasping Critical Area (GCA) | The area on the carton enclosed by the hand when first gripping. It is defined as follows:<br>1. At a frame when the hand is fully grasping the carton draw a line between the base of the thumb and the right border of the carton parallel to the lower border of the thumb.<br>2. Draw another line between the highest visible point of the index finger and the lateral border of the carton, parallel to the thumb.<br>3. Draw a line, parallel with the carton's long edge, from the base of the carton to the top of the carton passing by the end of the thumb tip.<br>4. GCA is the area confined between the three lines and the left border of the carton. |  |

| | | |
|---|---|---|
| Above GCA | The area on the carton above the upper border of the GCA, excluding the area that the spout occupies. |  |
| Below GCA | The area on the carton below the lower border of the GCA. |  |
| Adjacent to GCA | The area on the carton which is adjacent to GCA. It is bounded by the line running parallel to the upper border of the GCA, right border of the GCA and the line running parallel to lower border of the GCA. |  |
| Above Carton | The area located directly above the carton. |  |
| Spout | The area occupied by the spout and white area around the spout. |  |
| Glass | The area that the outer part of the glass occupies (this excludes the rear half of brim and any inner part of the glass). |  |

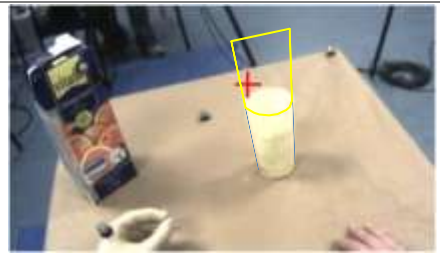
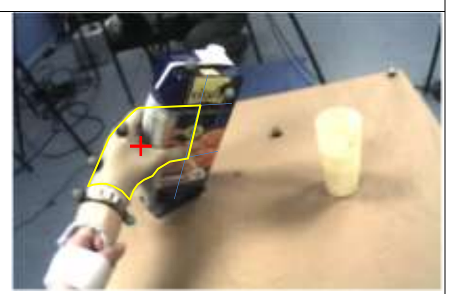
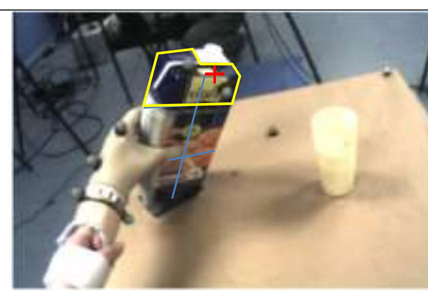
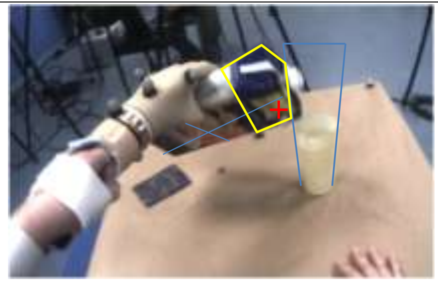
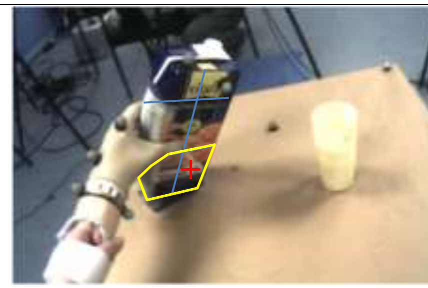
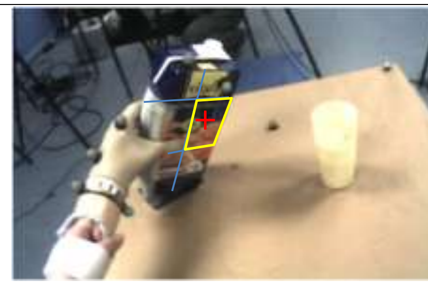
| | | |
|---|---|---|
| Above Glass | An area located directly above the glass, with its two sides being defined by lines extending from each edge of the glass. Its lower boundary is the front half of the brim of the glass. The upper boundary is defined by a line running approximately parallel to the table, starting at the highest point on the carton when it intersects with the area above the glass, during pouring. |  |
| Other | The area that does not belong to any of the other AOIs. | N/A |
| Missing Data (MD) | When the gaze indicator disappears. | N/A |

Table A. 1: The AOIs of the reaching phase.

| **AOIs** | **Definition** | **Example** |
|---|---|---|
| Grasping Critical Area (GCA) | As defined in Table A. 1, but in this phase also including the Hand AOI. |  |
| Above GCA | As defined in Table A. 1 excluding the part of the carton that overlaps with Above Glass AOI whilst pouring. |  |

| | | |
|---|---|---|
| | |  |
| Below GCA | As defined in Table A. 1. |  |
| Adjacent to GCA | As defined in Table A. 1. |  |
| Above Carton | As defined in Table A. 1 as long as the fixation is not at Above Glass AOI. |  |
| Following Carton | An AOI that exists when the point of regard is close to the boundary of the carton and moving with the hand | |
| Spout | As defined in Table A. 1 as long as the area does not overlap with Above Glass. |  |

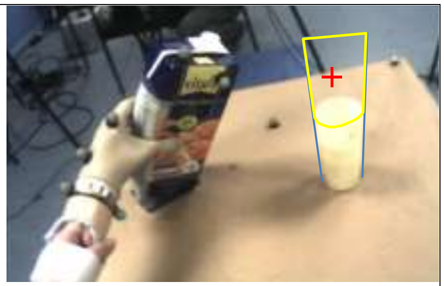
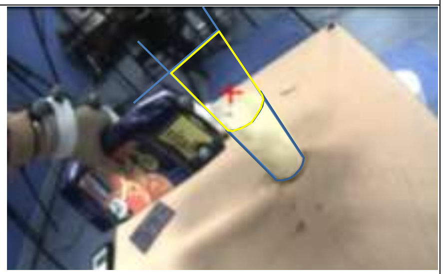
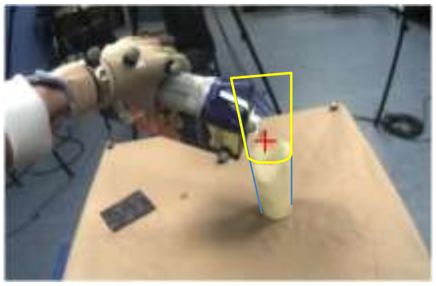
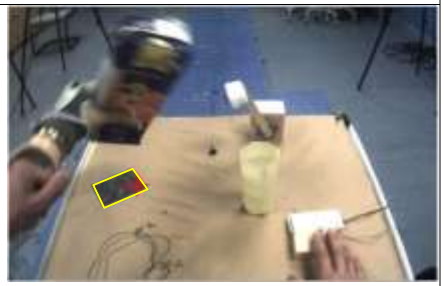
| | | |
|---|---|---|
| Above Glass | As in defined Table A. 1. |  |
| Glass | As defined in Table A. 1. |  |
| Pouring Critical Area (PCA) | The area that is related to pouring process which comes into existence the moment the upper part of the carton (SP or AGC) intersects with the Above Glass AOI. The PCA replaces AGL for the duration during which any of the upper carton intersects with the area above the glass. The area ceases to exist as soon as the upper part of the carton leaves the area above the glass. |   |
| Carton End-Point | The area on the table at which the carton is placed. |  |
| Other | As defined in Table A. 1. | N/A |
| Missing Data | As defined in Table A. 1. | N/A |

Table A. 2: AOIs of the manipulation phase.

### A.1. The confusion matrix

Table A. 3 represents a confusion matrix which helps to identify an AOI when AOIs overlap.

| | GCA | Above GCA | Below GCA | Adjacent GCA | Above Carton | F Carton | Hand | F Hand | Spout | Glass | Above Glass | PCA | Carton End-Point | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GCA | | - | - | - | - | GCA | GCA | F Hand | - | - | - | - | - | GCA |
| Above GCA | - | | - | - | - | Above GCA | Hand | F Hand | - | - | PCA | PCA | - | Above GCA |
| Below GCA | - | - | | - | - | Below GCA | Hand | F Hand | - | - | - | - | Below GCA | Below GCA |
| Adjacent GCA | - | - | - | | - | Adjacent GCA | Hand | F Hand | - | - | - | - | - | Adjacent GCA |
| Above Carton | - | - | - | - | | F Carton | Hand | F Hand | - | - | - | - | - | Above Carton |
| F Carton | GCA | Above GCA | Below GCA | Adjacent GCA | F Carton | | - | - | Spout | - | - | - | - | F Carton |
| Hand | GCA | Hand | Hand | Hand | Hand | - | | Hand | - | - | - | - | - | Hand |
| F Hand | F Hand | F Hand | F Hand | F Hand | F Hand | - | Hand | | - | - | - | - | - | F Hand |
| Spout | - | - | - | - | - | Spout | - | - | | - | PCA | PCA | - | Spout |
| Glass | - | - | - | - | - | - | - | - | - | | - | - | - | Glass |
| Above Glass | - | PCA | - | - | - | - | - | - | PCA | - | | PCA | - | Above Glass |
| PCA | - | PCA | - | - | - | - | - | - | PCA | - | PCA | | - | PCA |
| Carton End-Point | - | - | Below GCA | - | - | - | - | - | - | - | - | - | | Carton End-Point |
| Other | GCA | Above GCA | Below GCA | Adjacent to GCA | Above carton | F. carton | Hand | F Hand | Spout | Glass | Above glass | PCA | Carton End-Point | |

Table A. 3: Confusion matrix of the AOIs.

## Appendix B: Validation of simulated accelerometer data

### B.1. Introduction

This Appendix describes a short study to demonstrate that the acceleration signals calculated from marker data using the method described in Section 4.3.2.1, were an accurate representation of accelerations measured using a commercial 3 axis accelerometer; Xsens MTi sensors (XSENS, Xsens Technologies B.V., Enschede, The Netherlands). The methods are based on a previous study conducted at the University of Salford (214).

### B.2. Methods

#### *B.2.1. Instrumentation and setup*

##### *B.2.1.1. Xsens MTi sensors*

Xsens MTi sensor (XSENS, Xsens Technologies B.V., Enschede, The Netherlands) is a miniature light weight (50 g) inertial unit contains 3D accelerometers, gyroscopes and magnetometers, all integrated in 58 x 58 x 22 mm plastic housing (see Figure B. 1). For the purpose of this study, 3D acceleration data from accelerometers whose measurement range was ±2 $g$ (1$g$= 9.81 m/s$^2$) were sampled at 100 Hz. The sensor is powered through a cable connected via USB to a laptop. This cable is also used to transmit gathered data to the laptop where they are displayed in real time, saved and further processed. The accelerometer measures the combined effects of linear accelerations and the gravitational acceleration.

##### *B.2.1.2. Vicon motion capture system and marker data*

Marker data were captured using a 9 camera Vicon motion capture system (Vicon Motion Systems, Los Angles, USA). cameras were arranged around a 60 x 60 x 68 cm table on which the experiment was conducted. The table’s surface was checked using a spirit level to ensure that its surface lay in the horizontal plane. The marker data were sampled at 100 Hz.

Three 6 mm reflective markers (M1, M2 and M3) were attached to the plastic housing of an Xsens MTi sensor, as shown in Figure B. 1. M1 was attached at on the surface of the MTi, approximately at the origin of its local coordinate frame. M2 was attached at a point at the edge of the MTi, approximately on the MTi’s local X axis. M3 was placed at a point on the edge of the MTi, approximately on the Y axis.

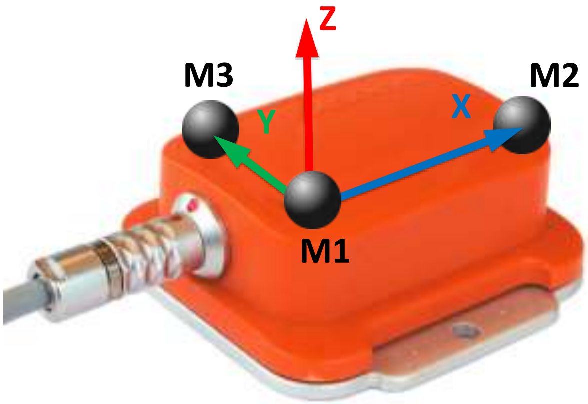



Figure B. 1: The Xsens MTi sensor with three reflective markers (M1, M2 and M3) attached to its plastic housing. Note, axes represent the local coordinate frame of the Xsens MTi sensor (adapted from (251)).

### *B.2.2. Data capturing*

Marker and accelerometer data were captured in two separate computers. To align the signals from both systems in time, a pulse signal sent from the Xsens system and captured by one of the Vicon analogue channels, was used to synchronize the Xsens and Vicon data. This pulse signal was provided at the beginning of each data capture.

For this validation study, three static and one dynamic trial were gathered, each lasting a few seconds. The static trials were collected while one of the axes of the sensor's coordinate frame was perpendicular to the table's surface as follows:

Trial 1: While the X axis of the local coordinate frame of the MTi sensor was perpendicular to the table's surface pointing upwards;

Trial 2: While the Y axis of the local coordinate frame of the MTi sensor was perpendicular to the table's surface pointing upwards;

Trial 3: While the Z axis of the local coordinate frame of the MTi sensor was perpendicular to the table's surface pointing upwards.

For the dynamic trial, the MTi sensor was firstly placed on the table, so the Z axis was pointing upwards, then the sensor was lifted off the table then rotated by the researcher around the X, Y and Z local axes of the sensor, in a random sequence.

### *B.2.3. Data analysis*

Marker data were processed as described in Chapter 4. Briefly, the marker data were labelled in Vicon workstation software *v*. 5.1 (Vicon Motion Systems, Los Angles, USA) then exported to SMAS (a custom-written MatLab software package) (213) for subsequent processing. In SMAS, marker data were interpolated and then filtered using a 4$^{th}$ order Butterworth filter with a cut-off frequency of 6 Hz.

Following this, the 3D linear acceleration of the marker approximately coinciding with the origin of the MTi sensor (M1) was calculated. For this purpose, a local coordinate frame was defined with its origin at M1as follow:

$X = (M2 - M1)/\| (M2 - M1)\|$

$I = (M2 - M1) \times (M3 - M1)$

$Z = I/\|I\|$

$Y = Z \times X$

This resulted in a coordinate frame that was approximately aligned with the coordinate frame of the MTi sensor. The position of the origin of the marker local coordinate frame was calculated in the global coordinate frame of the gait lab. By double differentiation of the position of the origin, the instantaneous acceleration at each instant in time was derived, expressed in the global co-ordinate frame. To account for the gravity acceleration, a value of 9.81m/s$^2$ was added to the vertical component of the acceleration. Finally, to simulate the outputs of an actual accelerometer, the calculated accelerations (with added gravity) were transformed to the marker local coordinate frame.

The captured linear acceleration signals from the MTi sensor (without any further processing) were then compared with those calculated from the marker data.

### *B.2.4. Statistical analysis*

For the dynamic trial, each pair of actual and simulated acceleration singles were compared using Pearson’s correlation coefficient ($r$) and RMS error ($\varepsilon$).

### B.3. Results

Figure B. 2 shows the acceleration signals from the MTi sensor and simulated acceleration signals from marker data for the three static trials.

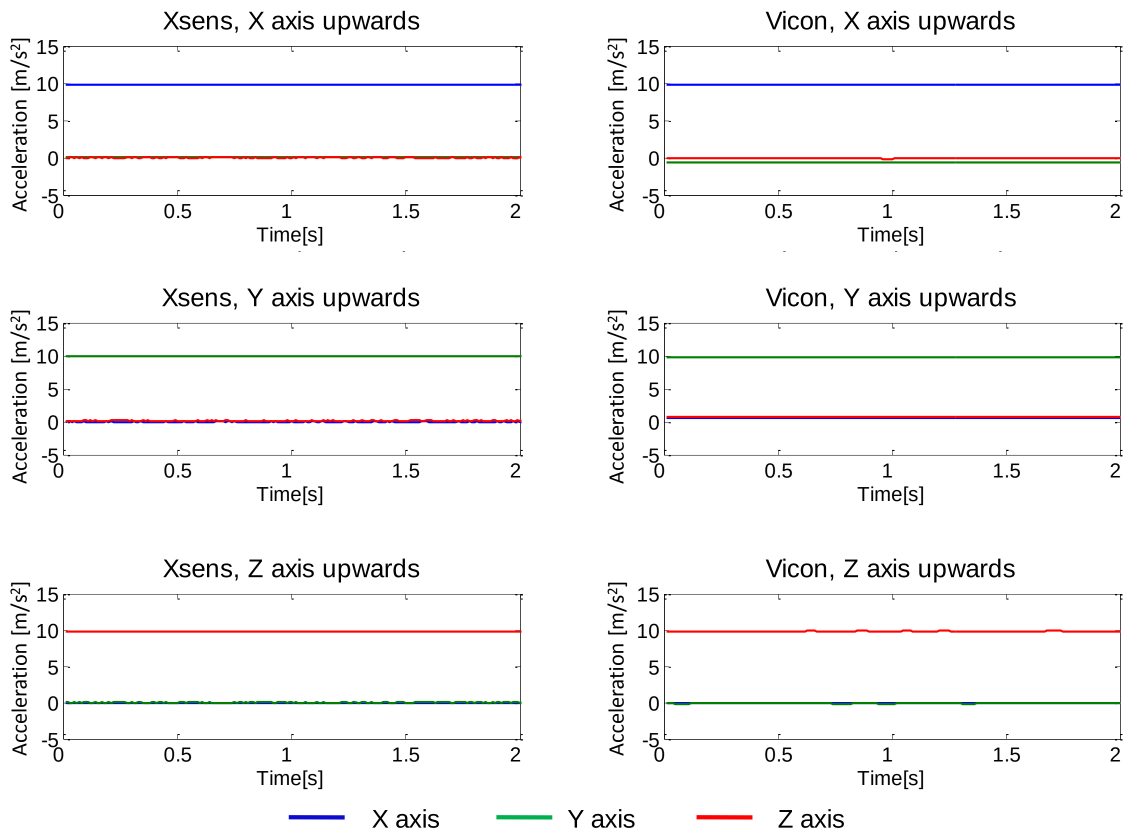



Figure B. 2: Acceleration signals obtained from MTi (left) and calculated from Vicon marker data (right) from the three static trials.

Figure B. 3 shows an example window on the X, Y and Z acceleration signals from both MTi and Vicon marker data.

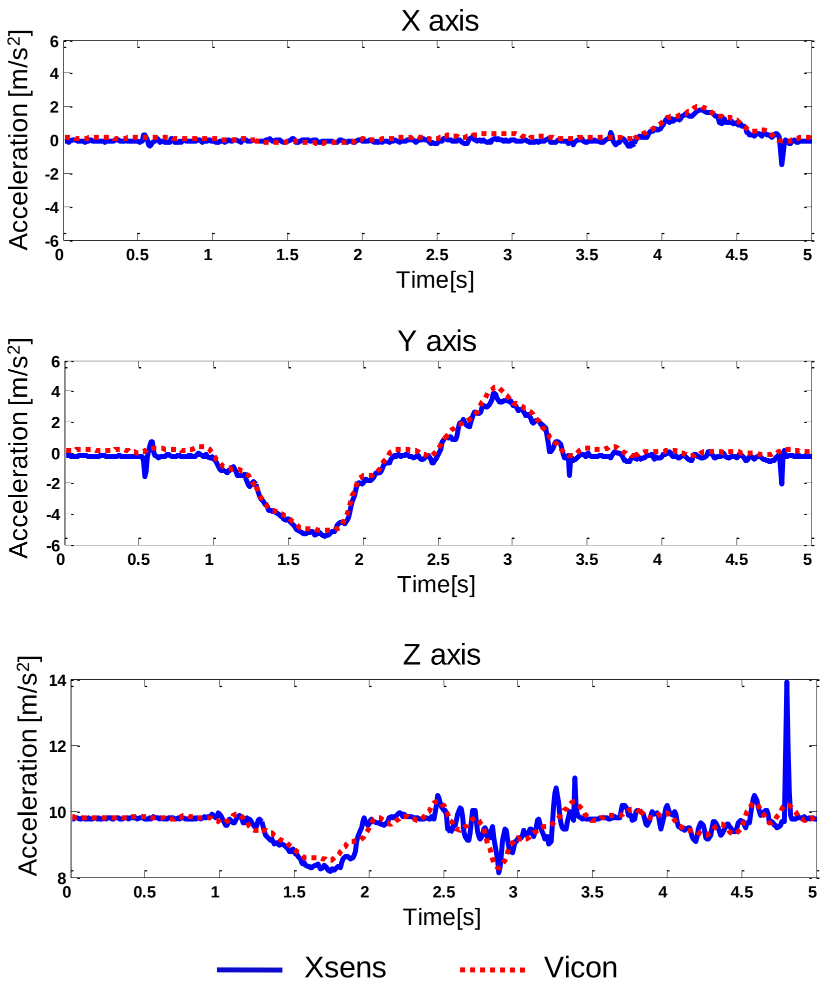



Figure B. 3: The acceleration trajectories obtained from Xsens MTi (sold line) and calculated from Vicon marker data (dashed line) during the dynamic condition.

Table B. 1 shows Pearson's correlation coefficients and RMS errors between each pair of acceleration trajectories (Vicon-derived and Xsens MTi).

| | X axis | Y axis | Z axis |
|---|---|---|---|
| Pearson's correlation coefficient | 0.87 | 0.96 | 0.81 |
| RMS error [$m/s^2$] | 0.34 | 0.49 | 0.41 |

Table B. 1: Comparison between the acceleration trajectories obtained from MTi sensors and calculated from Vicon marker data via Pearson's correlation and RMS error.

### B.4. Discussion and conclusions

The results from the static trials, (Figure B. 2) showed that the Vicon marker coordinate system and MTi local coordinate system were reasonably well aligned, as illustrated by the similarity in static results. Small differences are noticeable, particularly in the first trial (X-axis upwards), suggesting a small alignment discrepancy. Despite this, very similar acceleration waveforms were obtained from both measurement systems under the dynamic condition (Figure B. 3). The RMS error was relatively low and Pearson correlation coefficients quite high (Table B. 1). Observation suggests the differences were due to the minor misalignments evident from the static trials and differences in filtering between the two measurement systems.

In conclusion, this study demonstrated adequate validity of the simulated acceleration signals calculated from marker data collected by the Vicon motion capture system.

## Appendix C: Agreement between the two methods for calculating task and phase duration.

### C.1. Introduction

As the gaze data and kinematic data were collected by independent systems, a short study was conducted to evaluate the agreement between the two methods of calculating task and phase duration. Although data from the two systems were analysed separately, general conclusions on behaviours during each phase were drawn, based on both sets of data and hence it was useful to understand the extent to which datasets were aligned in time.

As a reminder, the onset and end of the task as well as the reaching and manipulation phases were defined from events that could be identified from both the gaze video and marker data. These events could be summarised as (see Section 4.3.2.1 for a more detailed definition):
Onset of reaching phase: The instant of time corresponding to the onset of the hand movement;
End of reaching phase/start of manipulation phase: The instant of time when the carton first leaves the table.
End of manipulation phase: The instant of time the hand releases the carton after task completion.

Algorithms for identifying task onset, phase transition and end of task enabled automated identification of these events from the kinematic data. However, the events from the gaze data had to be evaluated by visual inspection of the data. In this appendix, the differences between gaze-derived and kinematics-derived task and phase duration are reported.

### C.2. Methods

Gaze data from the first 5[§§§] subjects who participated in the study reported in Chapter 4 were analysed. As both the type of hand used and speed of completion may affect segmentation, trials from 3 sessions were included; V1 (baseline; using the anatomical hand), V2 (when the prosthesis was firstly introduced) and V4 (last evaluation session after completing all training sessions). All these trials were divided into two groups based on the type of the used hand; anatomical hand trials (V1 only), and prosthetic hand trials (V2 and V4).

[§§§] When the reliability investigation was carried out, data from only 5 subjects was available.

As stated in Chapter 4, in each V session, 12 trials were collected. However, for the analysis presented here, only those trials in which both marker data and gaze data were suitable for further analysis were included.

## C.3. Data analysis

For all included trials, the reaching and manipulation phase durations were calculated from the kinematic data as described in Chapter 4 (Section 4.3.2.1). For the gaze data, the onset and end of each phase as described above were identified by visual inspection of the gaze video data (Section 4.3.2.2).

For each trial, the values of the duration of the reaching and manipulation phases and task duration were then calculated. The duration of a phase was defined as the difference between the time at the end and onset of this phase, and task duration as the difference between the time at the end of the manipulation phase and the onset of reaching phase. This resulted in two duration values for each phase; one calculated from marker position data and another estimated from gaze video data. Task duration was the sum of both phase durations.

## C.4. Statistical analysis

In order compare the agreement between the paired duration values, Bland-Altman method was used, a commonly used method for assessing the agreement between two measurement approaches (252). For each duration (task, reaching and manipulation), the differences between the two measurements are plotted against the average of the two measurements. In all cases, the difference was time calculated from the gaze data was subtracted from time calculated from the kinematic data (253). Also the overall mean and standard deviation for both methods were calculated (253). The 95% confidence interval was defined as lying between the overall mean plus/minus 1.96 standard deviations (253).

## C.5. Results and discussion

For the analysis 46 trials from V1 were included, 47 trials from V2 and 49 trials from V4. Figure C. 1 shows the Bland-Altman plots of anatomical and prosthetic hand trials side by side. The durations of the reaching phase, manipulation phase and total task are plotted separately.

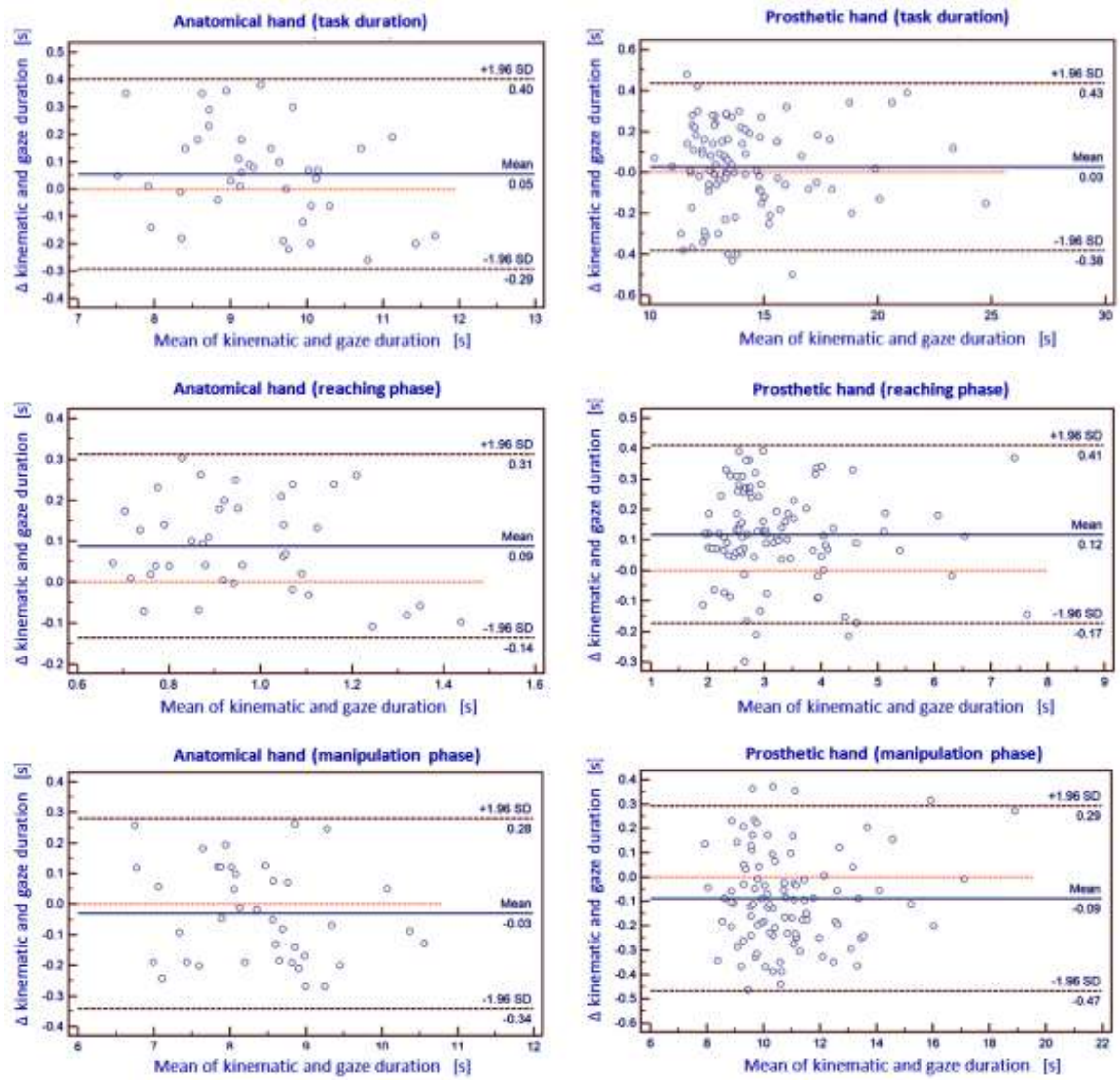



Figure C. 1: Bland-Altman plots showing the agreement between the two measurement methods to define task duration, reaching, manipulation phases for the anatomical (left) and prosthetic (right) hand.

The agreement for overall average task duration was good, with mean differences of 0.05 seconds (0.5% of the task duration) and 0.03 seconds (0.2% of the task duration), and confidence intervals of 0.35 seconds (3.7% of the task duration) and 0.4 seconds (2.8% of the task duration) for the anatomical and prosthetic hand respectively. This suggests no systematic bias between methods in calculating overall task duration and satisfactory levels of agreement between methods.

However, there was evidence of a small systematic bias in the calculation of each phase. Regardless of hand type, the mean reaching phase was slightly longer when calculated from kinematics, than when calculated from gaze (on average 0.09 s for the anatomical hand data and 0.12 for the prosthetic hand data). In turn, the mean manipulation phase was slightly shorter (on average 0.05 s for the anatomical hand data and 0.09 s for the prosthetic hand). One possible explanation for these observations would be early identifications of the start and end of the task from the kinematic data, compared to gaze and similar identifications of the phase transition events.

However, there was a reasonably high variance in the data. This suggested that some reaching trials in the anatomic hand condition showed a difference in duration of over 30%.

Considering the mean values for difference in durations, it can be seen that the agreement between the two measurement methods was consistently slightly higher for the anatomical hand data (V1) than for prosthetic hand data.

### C.6. Conclusions

The maximum reported mean error (difference between methods) in phase or overall task duration was 120 ms equivalent to 3 frames of the gaze data (1 frame = 40 ms). This showed there was no major bias between methods. However, the relative spread of the data about the mean was particularly high in one phase, namely anatomical reaching. In this phase, the confidence interval was around 20% of the mean. However, a visual check of the gaze sequences (Appendix I) during anatomical hand reach, suggest the spread of the data appeared to have relatively limited influence on the general patterns. That is, gross similarities between trials can be observed.

# Appendix D: Ethical approval letters

**Academic Audit and Governance Committee**

**Research Ethics Panel**
**(REP)**

THE UNIVERSITY OF SALFORD

**MEMORANDUM**

| | |
|---|---|
| **To** | Mohammad Medhat Dawd Sobuh |
| **cc:** | Dr Laurence Kenney, Ms Sue Braid |
| **From** | Tim Clements, Contracts Administrator |
| **Date** | 5th March 2010 |

**Subject:** **Approval of your Project by REP**

**Project Title:** **Visuo-motor aspects of learning to use a myoelectrically controlled upper limb prosthesis**

**RGEC Reference:** **REP09/174**

Following your responses to the Panel's queries, based on the information you provided, I can confirm that they have no objections on ethical grounds to your project.

If there are any changes to the project and/or its methodology, please inform the Panel as soon as possible.

Regards,

T. Clements

Tim Clements
Contracts Administrator
TC/JH

For enquiries please contact
Tim Clements
Contracts Administrator
Contracts Office
Enterprise Division
Faraday House
Telephone 0161 295 6907 Facsimile 0161 295 5494
E-mail: t.w.clements@salford.ac.uk

**Academic Audit and Governance Committee**

**Research Ethics Panel**
**(REP)**

| | |
|---|---|
| **To** | Mohammad Medhat Dawd Sobuh |
| **cc:** | Dr L Kenney, Ms Sue Braid |
| **From** | Jayne Hunter, Contracts Administrator |
| **Date** | 8th April 2011 |

---

**Subject:** **Approval of your Project by REP**

**Project Title:** **A preliminary study of gaze behaviour and upper limb kinematics in trans-radial upper limb myoelectric prosthesis users and their relationships with function, activity and participation**

**REP Reference:** **REP11/028**

Following your responses to the Panel's queries, based on the information you provided, I can confirm that they have no objections on ethical grounds to your project.

If there are any changes to the project and/or its methodology, please inform the Panel as soon as possible.

Regards,

Jayne Hunter
Contracts Administrator

For enquiries please contact
Jayne Hunter
Contracts Administrator
Contracts Office
Enterprise Division
Faraday House
Telephone: 0161 295 3530 Facsimile: 0161 295 5494
E-mail: j.hunter@salford.ac.uk

**NHS**

## National Research Ethics Service

**NORTH WEST 10 RESEARCH ETHICS COMMITTEE – GREATER MANCHESTER NORTH**

3rd Floor, Barlow House
4 Minshull Street
Manchester
M1 3DZ
Tel: 0161 625 7817
Email: cynthia.carter@northwest.nhs.uk

Mr Mohammad Sobuh
PhD Student
University of Salford
Centre for Health, Sport and Rehabilitation Sciences Research
M6 6PU

25 March 2011

Dear Mr Sobuh

| | |
|---|---|
| **Study title:** | **A preliminary study of gaze behaviour and upper limb kinematics in trans-radial upper limb myoelectric prosthesis users and their relationships with function, activity and participation** |
| **REC reference:** | **11/NW/0060** |
| **Protocol number:** | **N/A** |

Thank you for your letter of 16 March 2011, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

**Confirmation of ethical opinion**

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

**Ethical review of research sites**

NHS sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

**Conditions of the favourable opinion**

The favourable opinion is subject to the following conditions being met prior to the start of the study.

<u>Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.</u>

*Management permission ("R&D approval") should be sought from all NHS organisations involved in the study in accordance with NHS research governance arrangements.*

Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at http://www.rdforum.nhs.uk.

*Where a NHS organisation's role in the study is limited to identifying and referring potential participants to research sites ("participant identification centre"), guidance should be sought from the R&D office on the information it requires to give permission for this activity.*

*For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.*

*Sponsors are not required to notify the Committee of approvals from host organisations*

**It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).**

**Approved documents**

The final list of documents reviewed and approved by the Committee is as follows:

| *Document* | *Version* | *Date* |
|---|---|---|
| Questionnaire: OPUS with UEFS module | | |
| Protocol | 1.0 | 06 February 2011 |
| Letter of invitation to participant | 1.1 | 16 March 2011 |
| REC application | 3.1 | 06 February 2011 |
| Response to Request for Further Information | 1 | 16 March 2011 |
| Summary/Synopsis | 1.0 | 06 February 2011 |
| Summary/Synopsis | 1.0 | 06 February 2011 |
| Questionnaire: TAPES | | |
| Participant Identification Sheet | 1.0 | 06 February 2011 |
| Participant Information Sheet | 1.1 | 16 March 2011 |
| Evidence of insurance or indemnity | | 01 August 2010 |
| Investigator CV | M Sobuh | 06 February 2011 |
| Participant Consent Form | 1.1 | 16 March 2011 |
| CV J Kulkarni | | 23 October 2010 |
| CV A Galpin | | 01 January 2011 |
| CV S Thies | | |

**Statement of compliance**

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees (July 2001) and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

**After ethical review**

Now that you have completed the application process please visit the National Research Ethics Service website > After Review

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

The attached document *"After ethical review – guidance for researchers"* gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

We would also like to inform you that we consult regularly with stakeholders to improve our service. If you would like to join our Reference Group please email referencegroup@nres.npsa.nhs.uk.

| 11/NW/0060 | Please quote this number on all correspondence |
|---|---|

With the Committee's best wishes for the success of this project

Yours sincerely

C. Carter

pp **Dr Peter Klimiuk**
**Chair**

Enclosures: "After ethical review – guidance for researchers" SL-AR2

Copy to: Dr Laurence Kenney (By email L.P.J.Kenney@salford.ac.uk)

Sue Braid, University of Salford (By email s.braid@salford.ac.uk)

**Appendix E: Statistical analyses (Chapter 4)**

1. **Main results of mixed ANOVA for all joints over the 3 testing days in reaching phase:**

Day effect: Sphericity assumed, $F(2,10)=1.04$, MSE=0.01, $p>.05$, $p=.389$.

Day x Joint ROM effect: Sphericity assumed, $F(6,30)=1.76$, MSE=0.03, $p>.05$, $p=.142$

2. **Main results of mixed ANOVA for all joints over the 3 testing days in manipulation phase:**

Day effect: Sphericity assumed, $F(2,10)=19$, MSE=1004.6, $p<.05$, $p=.0001$.

Day x joint: Sphericity assumed, $F(6,30)=32.7$, MSE=1022.1, $p<.05$, $p=.0001$

3. **Main results of mixed ANOVA for gaze duration at the aggregated AOIs over the 3 testing days:**

Day effect: Sphericity assumed, $F(2,12)= 6.4$, MSE=0.36, $p< .05$, $p= .013$

Day x AOI: Sphericity assumed, $F(4,24)=.45.55$, MSE=4.76, $p<.05$, $p= .0001$.

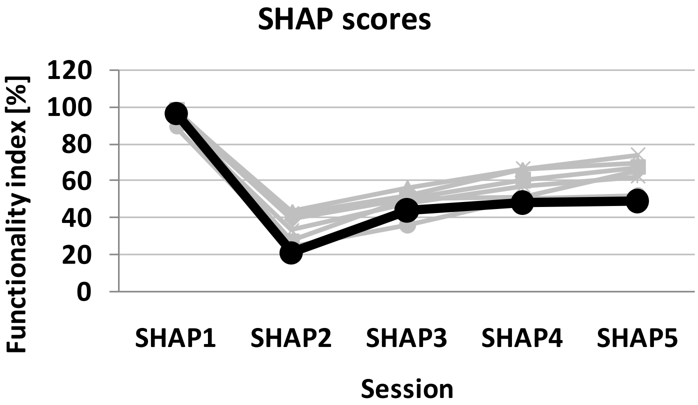
| Variable | Transformation | ANOVA | Within-subjects p-value correction | Prosthetic effect (V1 vs. V2) | Training effect (V2 vs. V4) |
|---|---|---|---|---|---|
| SHAP index | | $F(2,12)=283.35$, MSE=6888.14, $p<.05$, $p=.0001$ | Sphericity assumed | $F(1,6)=422.02$, MSE=27531.57, $p<.05$ $p=.0001$ | $F(1,6)=258.47$, MSE=6240.14, $p<.05$ $p=.0001$ |
| Task duration | Log10 | $F(2,12)=34.57$, MSE=0.1, $p<.05$, $p=.0001$ | Sphericity assumed | $F(1,6)=43.21$ MSE=0.38, $p<.05$, p=001 | $F(1,6)=11.45$, MSE=0.07, $p<.05$, p=015 |
| Shoulder flexion-extension (manipulation) | | $F(2,12)=1.9$, MSE=64.62, $p>.05$, $p=.2$ | Sphericity assumed | | |
| Shoulder adduction-abduction (manipulation) | | $F(2,12)=80.28$, MSE=3965.4, $p<.05$, $p=.0001$ | Sphericity assumed | $F(1,5)=123.03$, MSE=12637.2, $p<.05$, $p=.0001$ | $F(1,5)=0.55$, MSE= 49.45, $p>.05$ , $p=.49$ |
| Shoulder rotation (manipulation) | | $F(2,12)=.96$, MSE=28.17, $p>.05$, $p=.416$ | Sphericity assumed | | |
| Elbow flexion-extension (manipulation) | | F(2,12)=.37, MSE=12.61, $p>.05$, $p=.698$ | Sphericity assumed | | |
| Temporal variability (reaching) | | $F(2,12)=13.05$, MSE=2994.6, $p<.05$, $p=.001$ | Sphericity assumed | $F(1,6)= 15.12$, MSE= 11693.17, $p<.05$ $p=.008$ | $F(1,6)= 11.82$, MSE= 4719.13 $p<.05$, $p=.014$ |
| Temporal variability (manipulation) | | $F(2,12)=5.06$, MSE=3941, $p<.05$, $p=.026$ | Sphericity assumed | $F(1,6)= 6.28$, MSE= 14363.01, $p<.05$ $p=.008$ | $F(1,6)= 4.82$, MSE= 8526.17, $p>.05$ $p=.071$ |
| Spatial variability (reaching) | Reciprocal (1/x) | $F(2,12)=.47$, MSE=0.188, $p>.05$, $p=.636$ | | | |
| Spatial variability (manipulation) | | $F(2,12)=3.29$, MSE=.02, $p>.05$, $p=.073$ | Sphericity assumed | | |
| Time to peak aperture | | $F(1.28,7.68)=19.51$, MSE=3.25, $p<.05$, $p=.002$ | Huynh-Feldt corrections | $F(1,6)= 43.60$, MSE= 12.97, $p<.05$ $p=.001$ | $F(1,6)=4.95$, MSE=2.93, $p<.05$ $p=.001$ |

| | | | | | |
|---|---|---|---|---|---|
| Peak speed | | *F*(1.08,6.48)=35.35, MSE=0.17, p<.05, p=.0001 | Huynh-Feldt corrections | (*F*(1,6)=36.65, MSE= 0.30, p<.05, p=.001 | *F*(1,6)=8.80, MSE=0.003, p<.05, p=.025 |
| Time to peak speed | | F(2,12)=8.81, MSE=.86, p<.05, p=.004 | Sphericity assumed | *F*(1,6)= 20.15, MSE= 3.45, p<.05, p=.004 | (*F*(1,6)= 2.88, MSE= 0.98, p>.05, p=.141 |
| Number of transitions (reaching) | | *F*(2,12)=4.22, MSE=5.32, p<.05, p=.041 | Sphericity assumed | *F*(1,6)= 25.14, MSE= 20.15, p<.05 p=.002 | *F*(1,6)=3.59, MSE=10.02, p>.05 , p=.107 |
| Number of transitions (manipulation) | | *F*(2,12)=9.81, MSE=37.51, p<.05, p=.003 | Sphericity assumed | *F*(1,6)=20.70, MSE= 147.43, p<.05 p=.004 | *F*(1,6)=2.19, MSE=21.88, p>.05 , p=.189 |
| Gaze duration Above carton (reaching) | Log10 | *F*(2,12)=34.51, MSE=4.64, p<.05, p=.0001 | Sphericity assumed | *F*(1,6)=86.60, MSE= 25.08, p<.05 p=.0001 | *F*(1,6)=0.28, MSE= 0.11, p>.05 p=.615 |
| Gaze duration Hand related (reaching) | Log10 | *F*(2,12)=38.71, MSE=3.30, p<.05, p=.0001 | Sphericity assumed | *F*(1,6)=291.34, MSE=11.44, p<.05 p=.0001 | *F*(1,6)=2.41, MSE= 0.54, p>.05 p=.172 |
| Gaze duration GCA related (reaching) | Log10 | *F*(2,12)=42.83, MSE=1.95, p<.05, p=.0001 | Sphericity assumed | *F*(1,6)=39.83, MSE= 5.63, p<.05 p=.001 | *F*(1,6)=0.29, MSE= 0.01, p>.05 p=.609 |
| SHAP index | | *F*(2,12)=283.35, MSE=6888.14, p<.05, p=.0001 | Sphericity assumed | *F*(1,6)=422.02, MSE=27531.57, p<.05 p=.0001 | *F*(1,6)=258.47, MSE=6240.14, p<.05 p=.0001 |

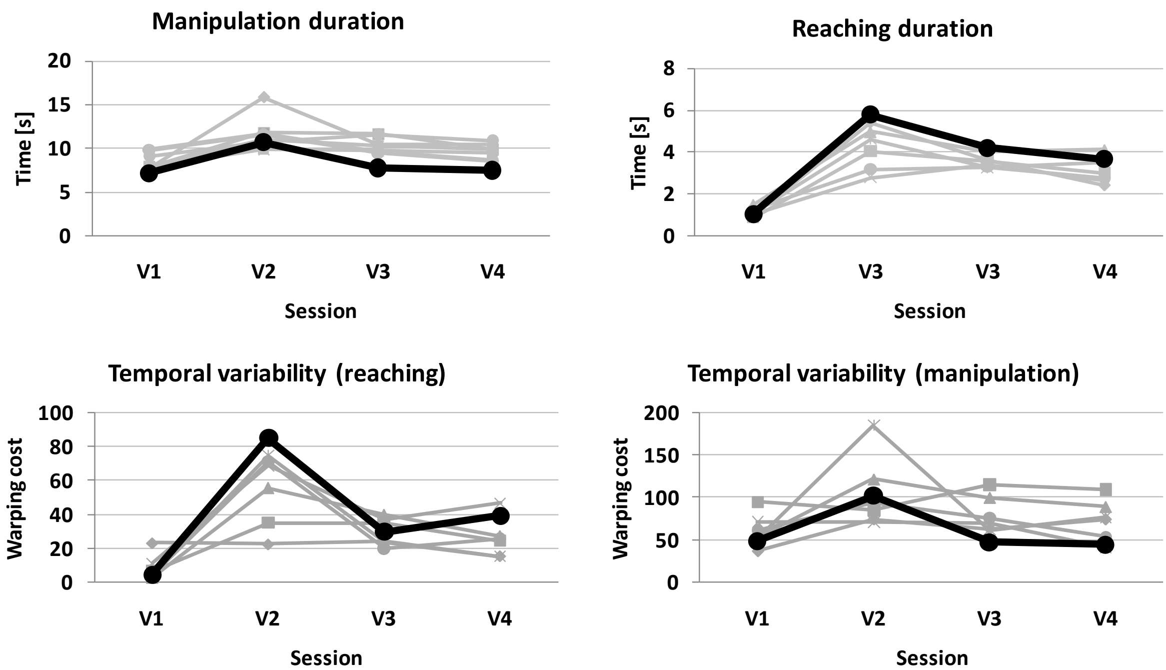
**Appendix F: Comparing visuomotor results of the left-handed subject with results of the other right-handed subjects (Chapter 4)**

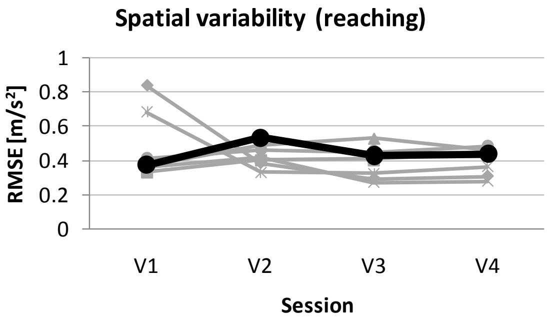
Note: Throughout this appendix, the left-handed subject's data are represented with black lines; other subjects' data are represented with gray lines.

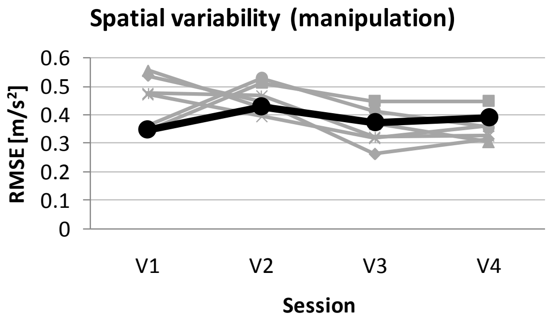
**F.1. SHAP scores**

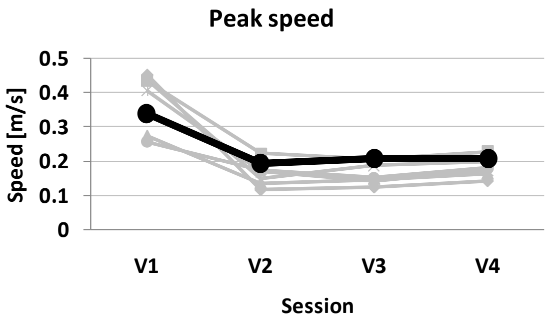


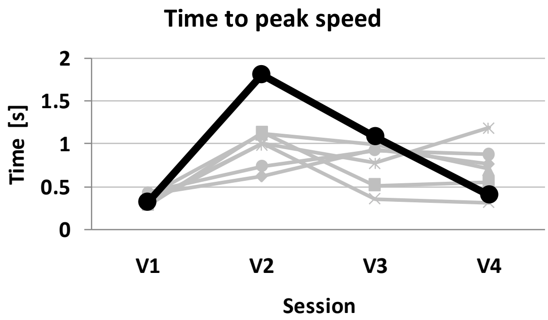

**F.2. Kinematic data**

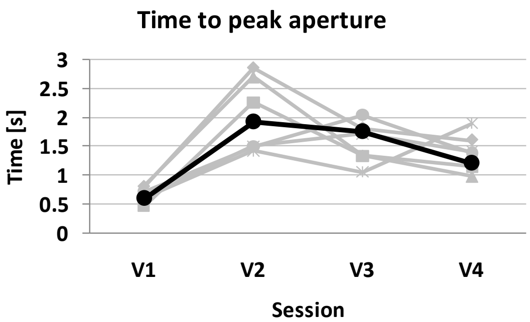




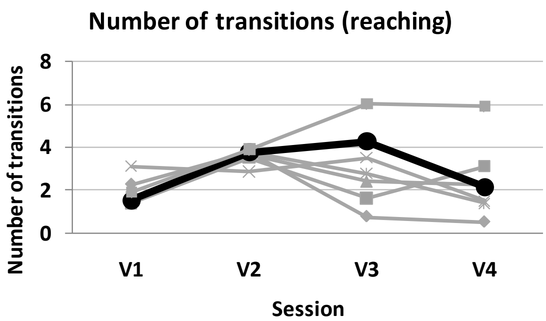



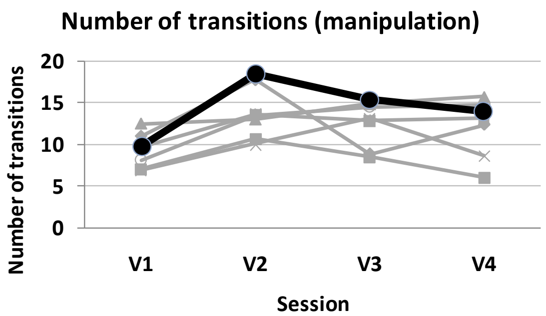




## F.3. Gaze data

Note, due to the large number of AOIs, gaze duration data are not presented here.



## Appendix G: The shoulder centre of rotation (SCR)

The shoulder is a complex joint comprising 4 sub-joints. Upper arm movement can be the result of rotation and/or translation motions at one or more of the 4 sub-joints of the shoulder (depending on the direction and the range of the movement) (254). Nevertheless, since the interest in this thesis is to define the gross changes to the upper arm movement resulting from using the prosthesis, only the resultant movement of the upper arm relative to the trunk was calculated. A similar approach to the one was adopted here was reported in earlier work on upper limb amputee kinematics (238), with the main difference lying in the definition of shoulder centre of rotation, or SCR (in the previous study , the SCR was assumed to be the most dorsal point on the acromioclavicular joint (238)).

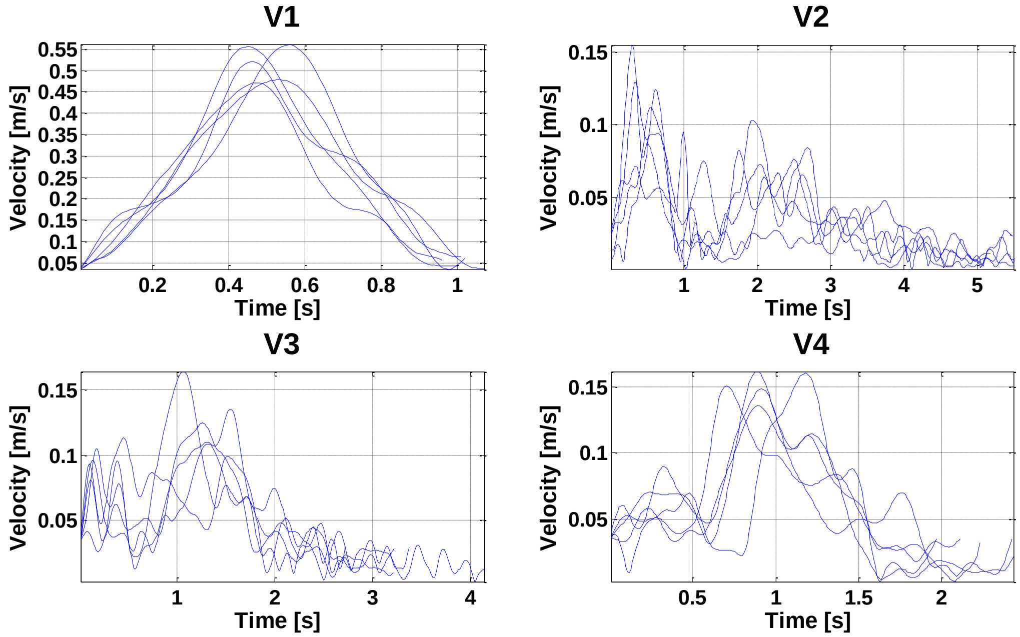
In this thesis, a virtual centre of rotation about which the upper arm rotates relative to the trunk was defined from data gathered in a functional trial. In the functional trial, marker data of the trunk and upper arm were collected while subjects completed a sequence of arm movements (see Section 4.2.1.2, Chapter 4).

This virtual centre of rotation was defined in Visual 3D using a pipeline written based on an experimental work by Schwartz and Rozumalski (255). Although the method was originally developed for estimating hip joint centre, it was judged to be a satisfactory approach for the purposes of the thesis.

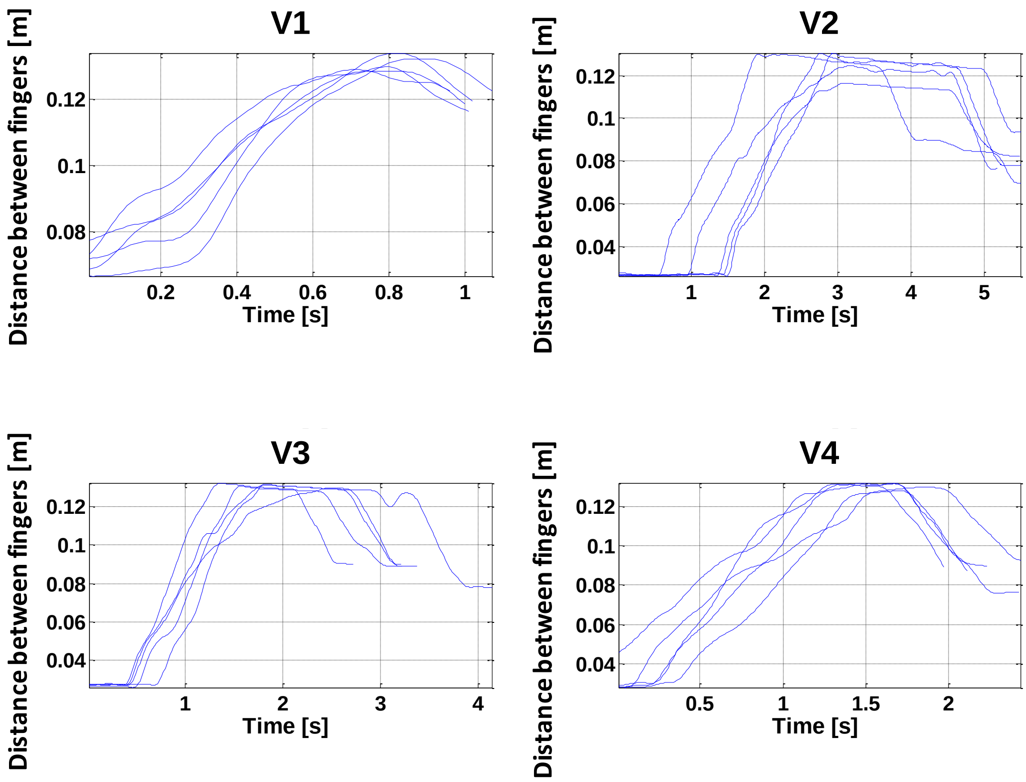
## Appendix H: Wrists velocity and hand aperture profiles (Chapter 4)

### Subject 1

### Velocity profiles

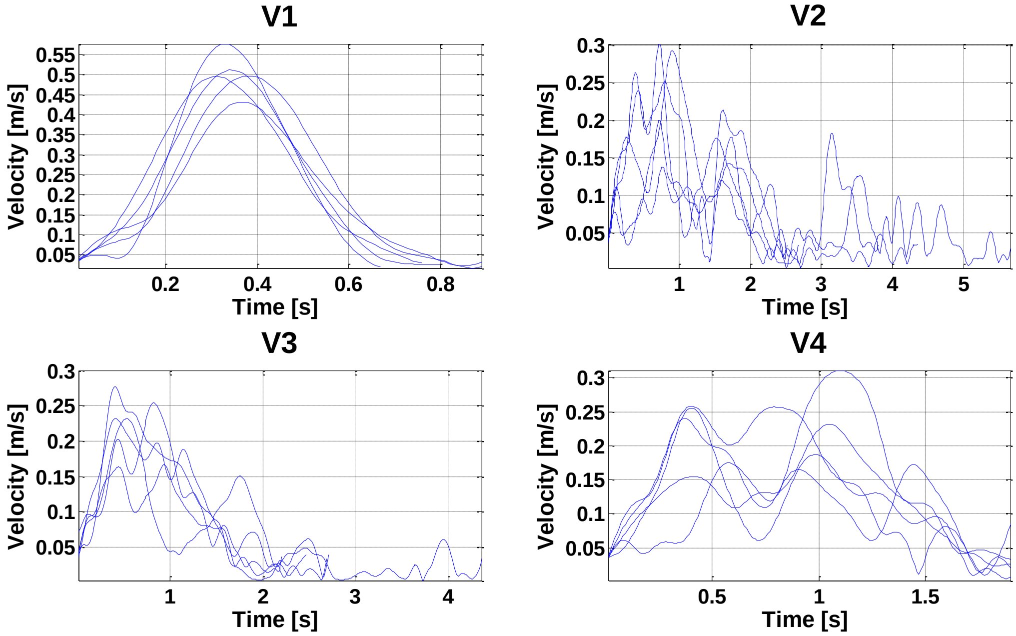



### Hand aperture profiles

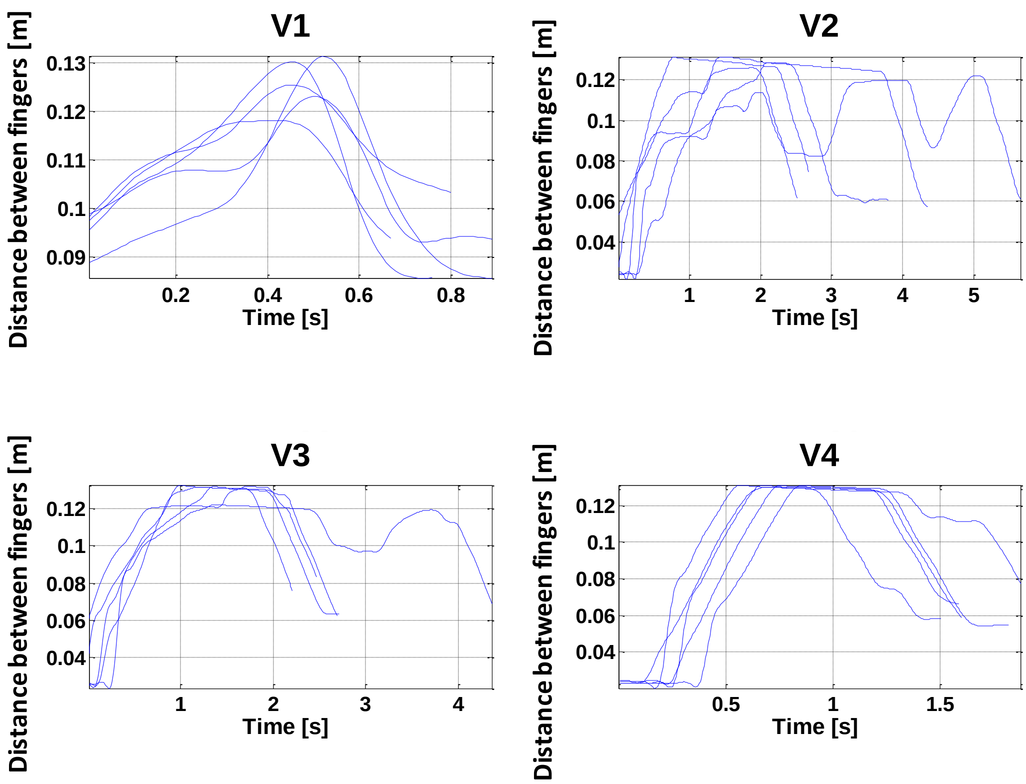


## Subject 2

### Velocity profiles

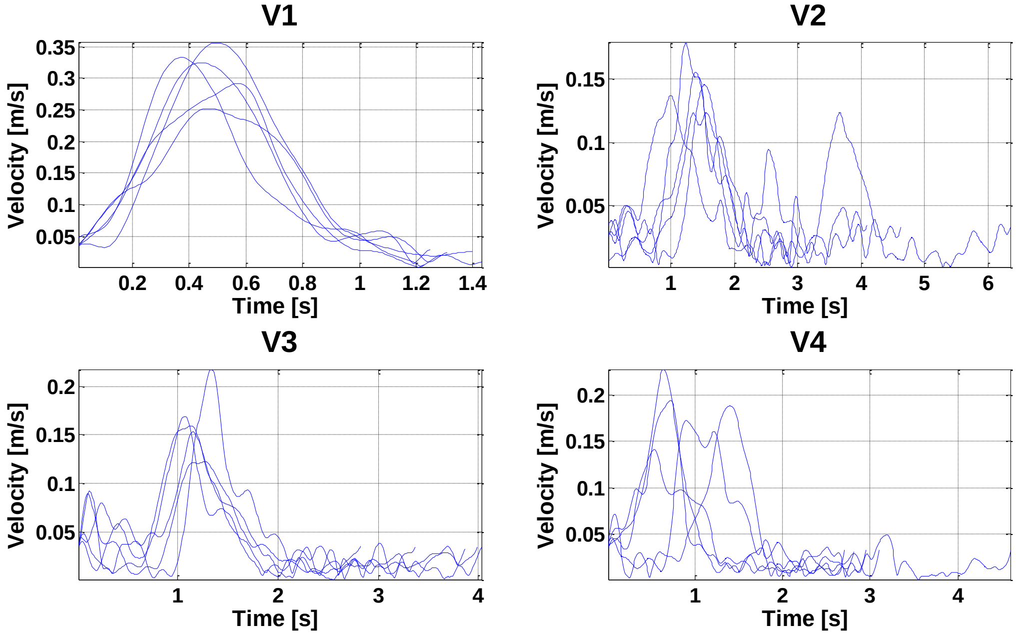



### Hand aperture profiles

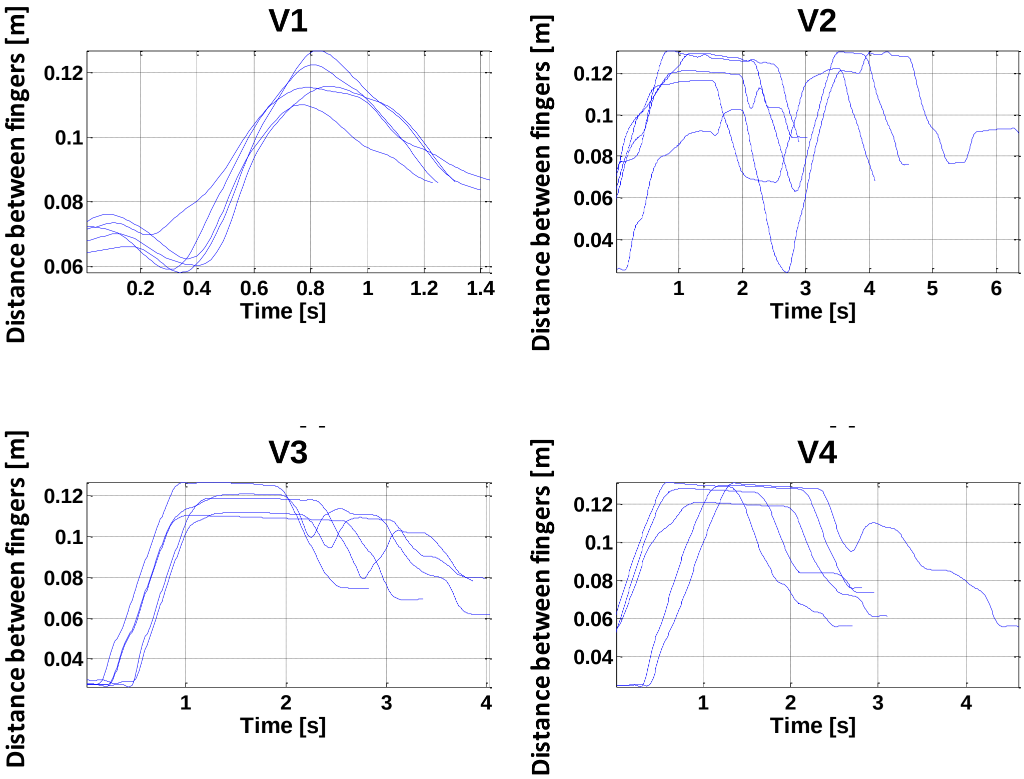


## Subject 3

### Velocity profiles

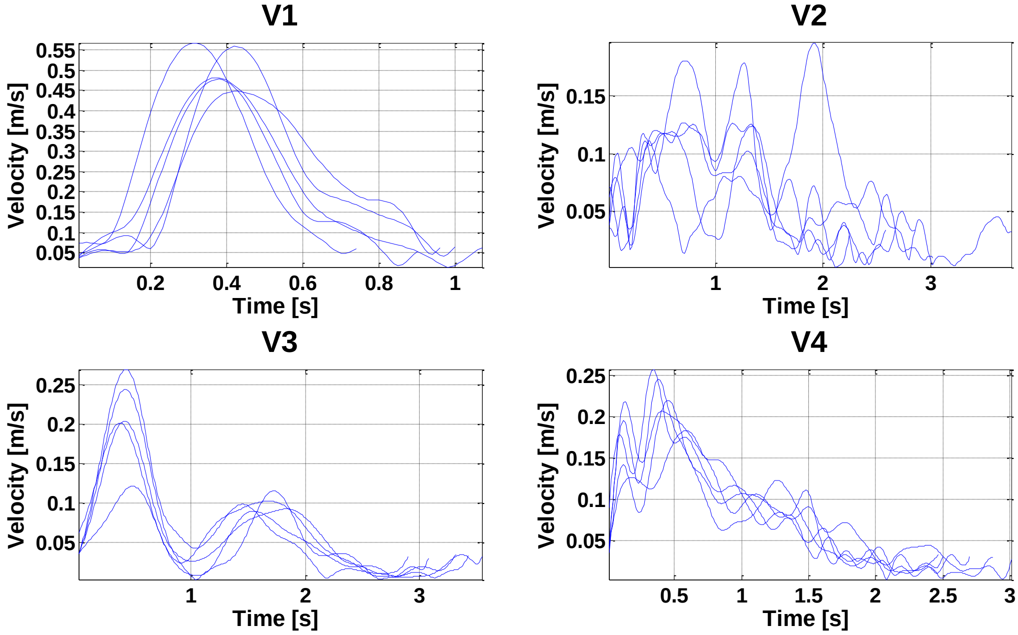



### Hand aperture profiles

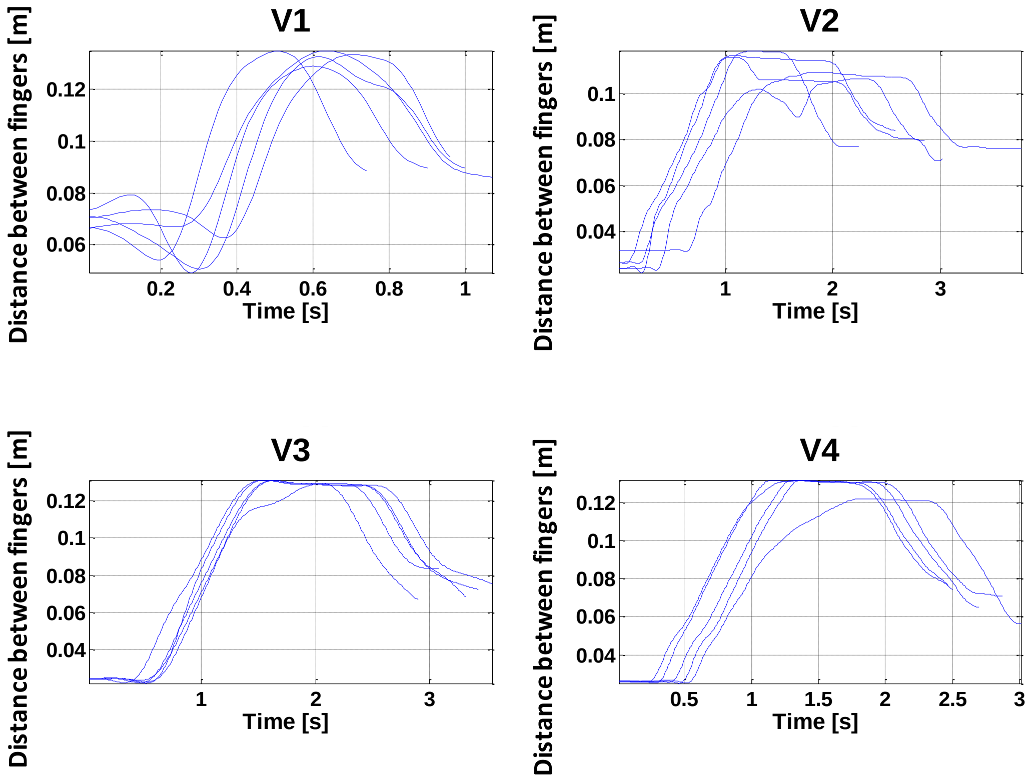


## Subject 4

### Velocity profiles

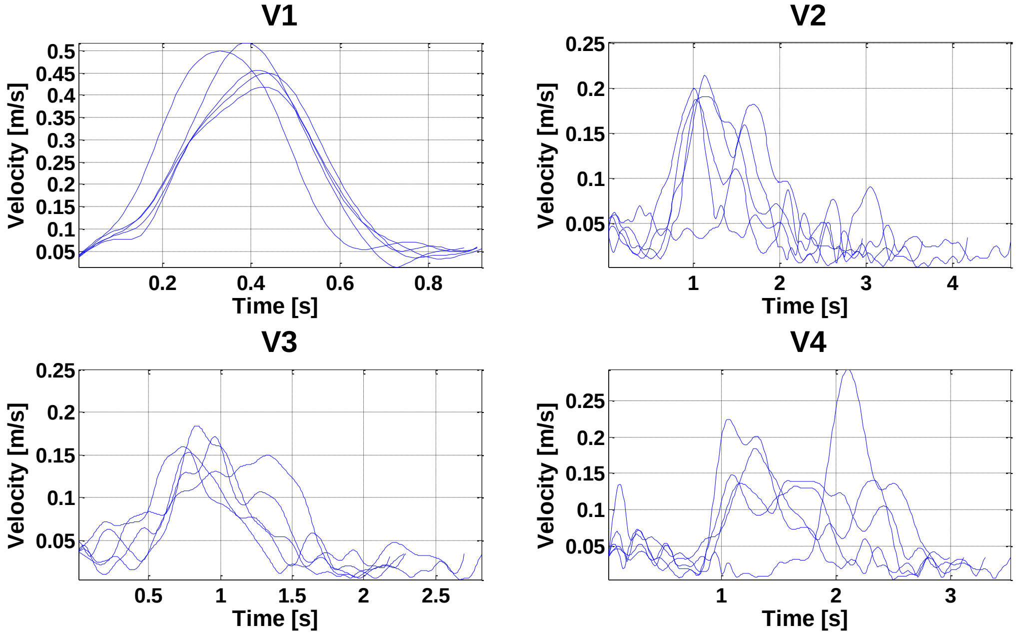



### Hand aperture profiles

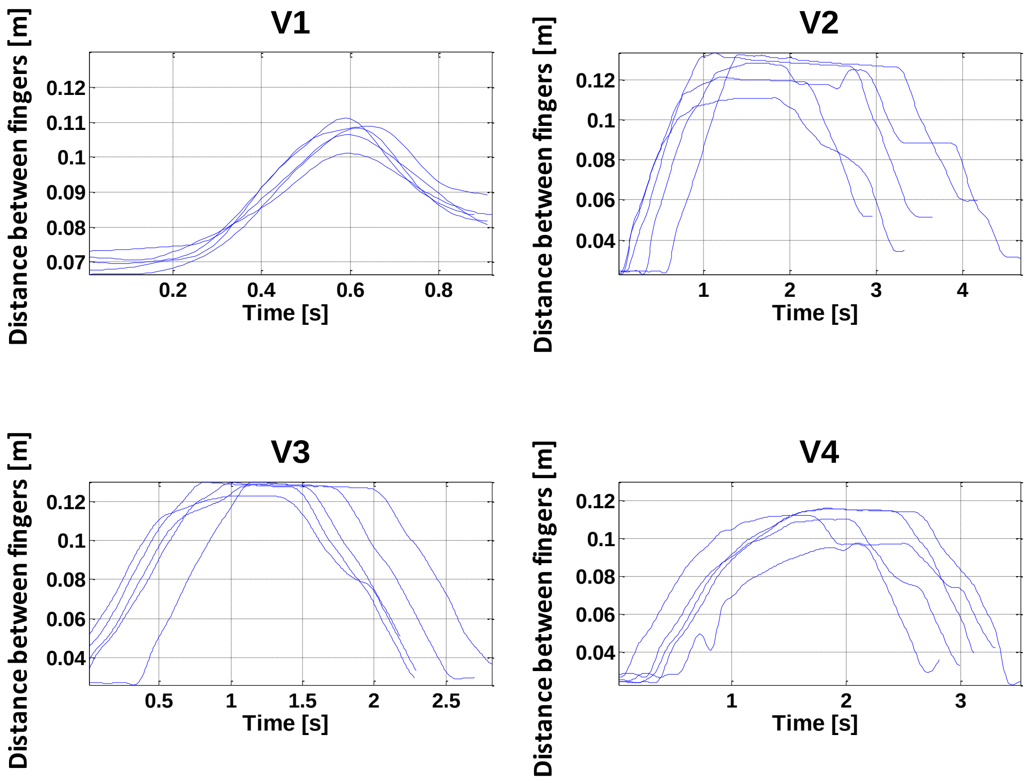


## Subject 5

### Velocity profiles

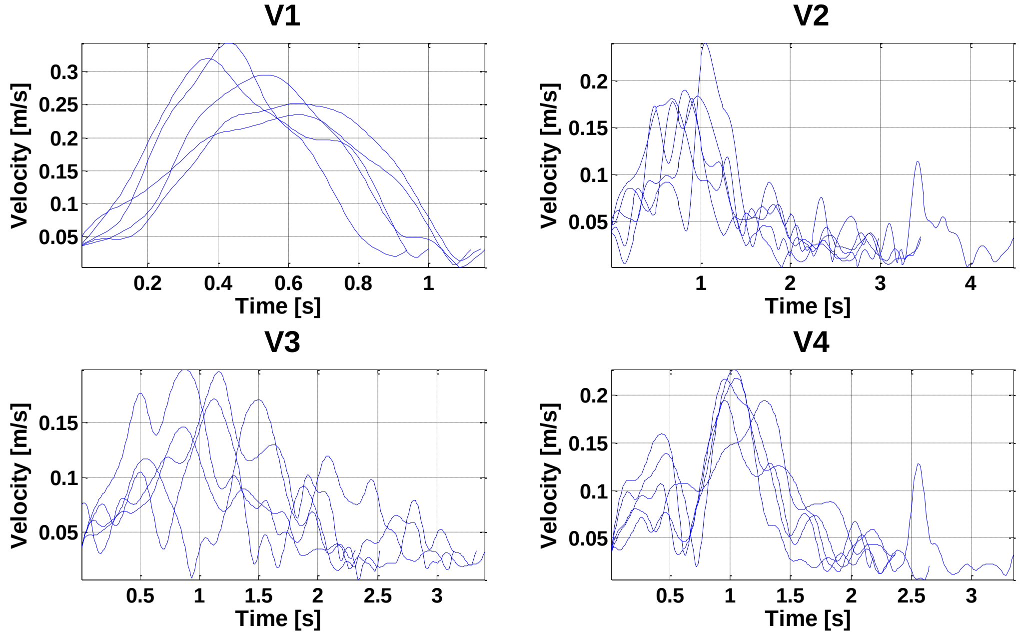



### Hand aperture profiles

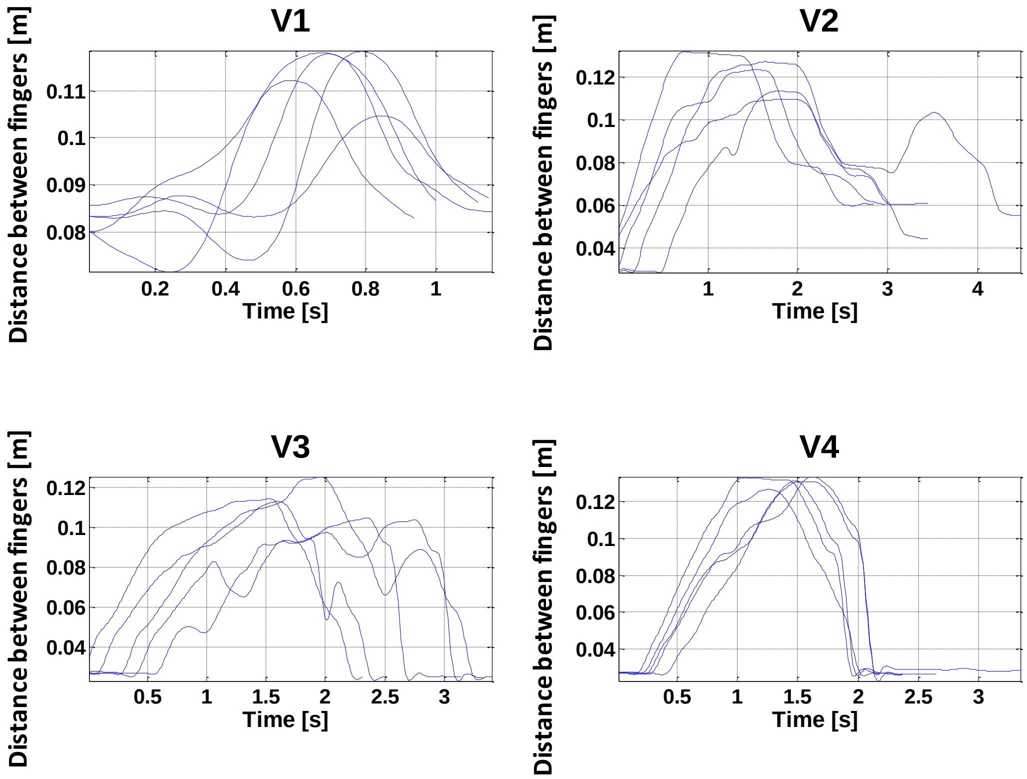


# Subject 6

## Velocity profiles

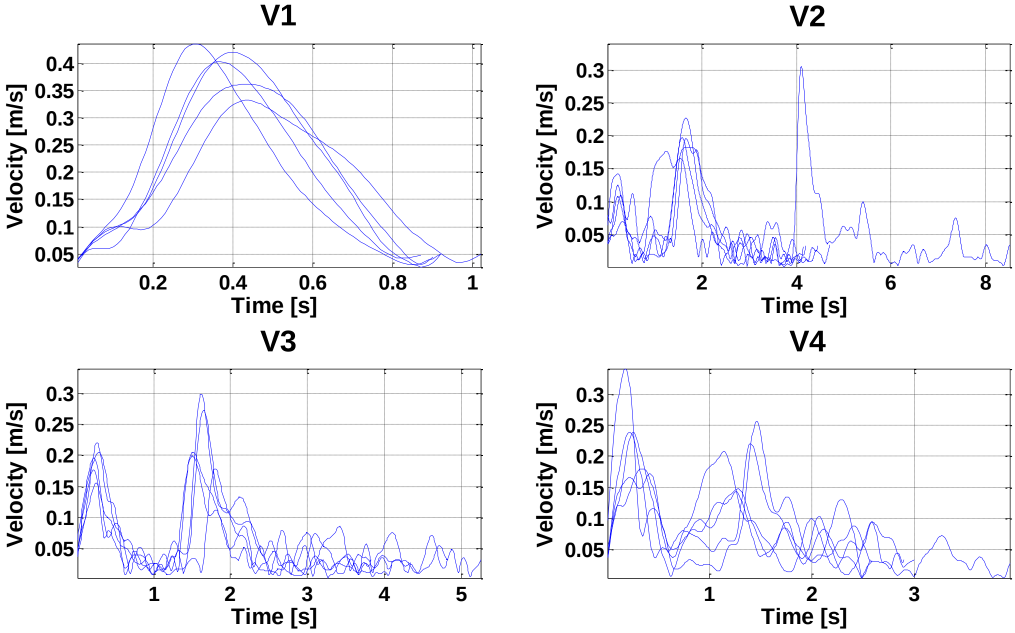



## Hand aperture profiles

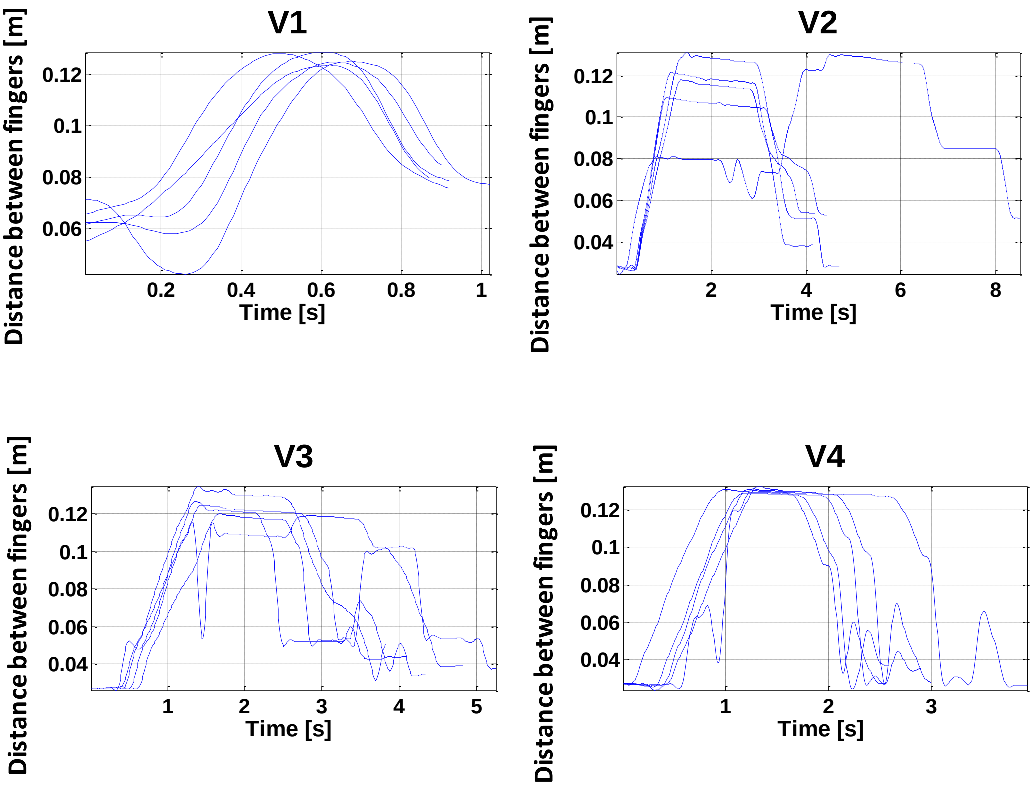


## Subject 7 (left handed)

### Velocity profiles

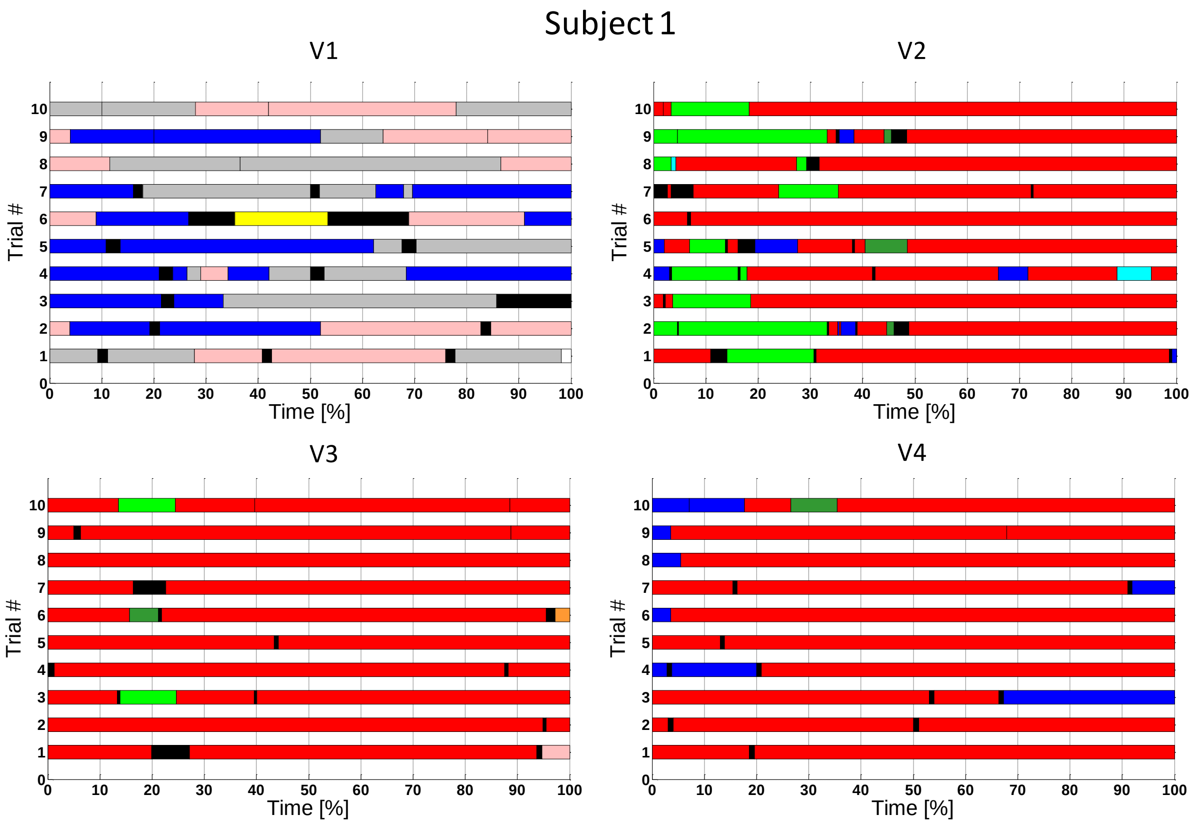


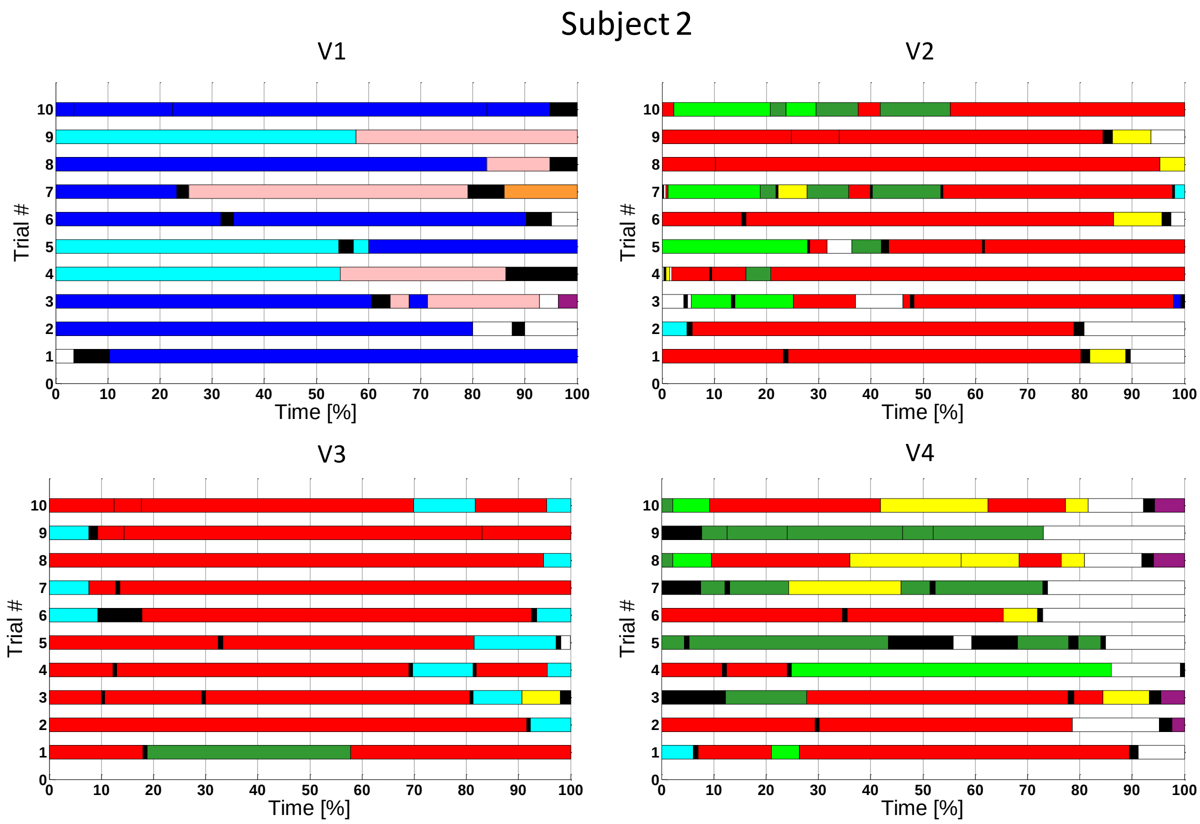

### Hand aperture profiles



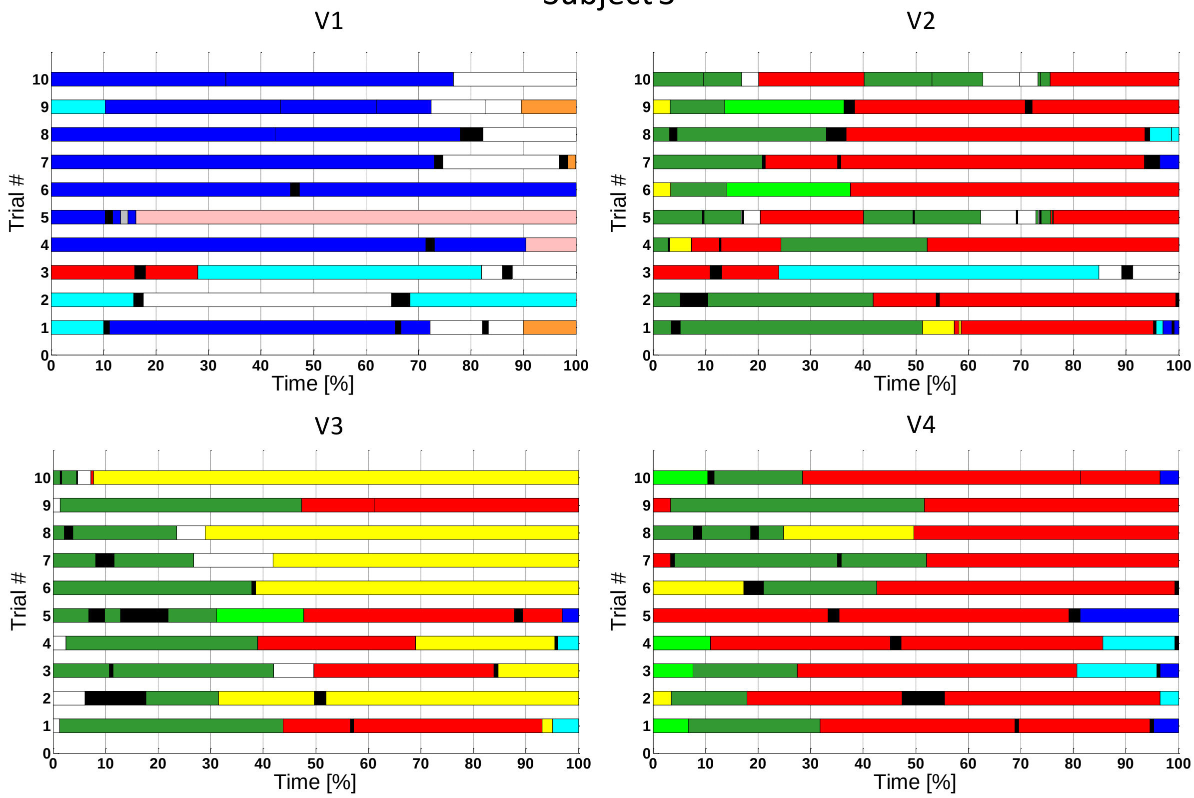
# Appendix I: Gaze sequence (Chapter 4)

## I.1. Reaching phase

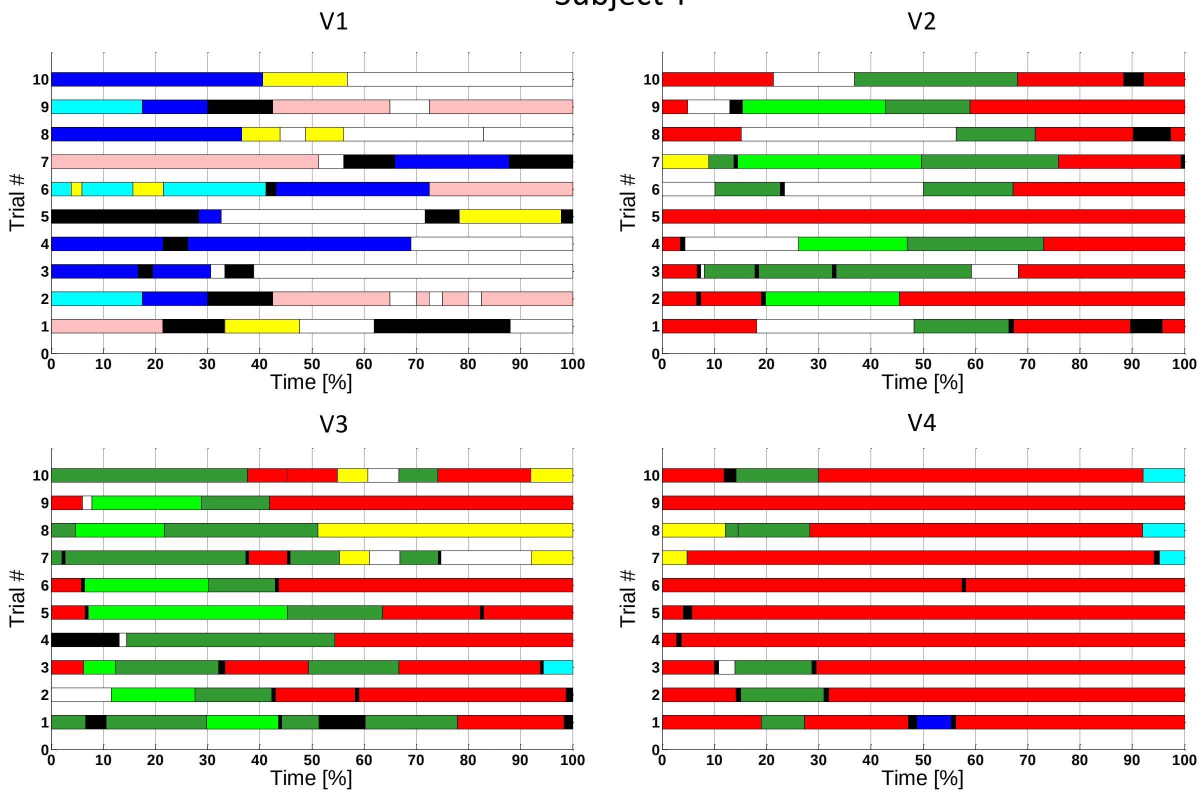


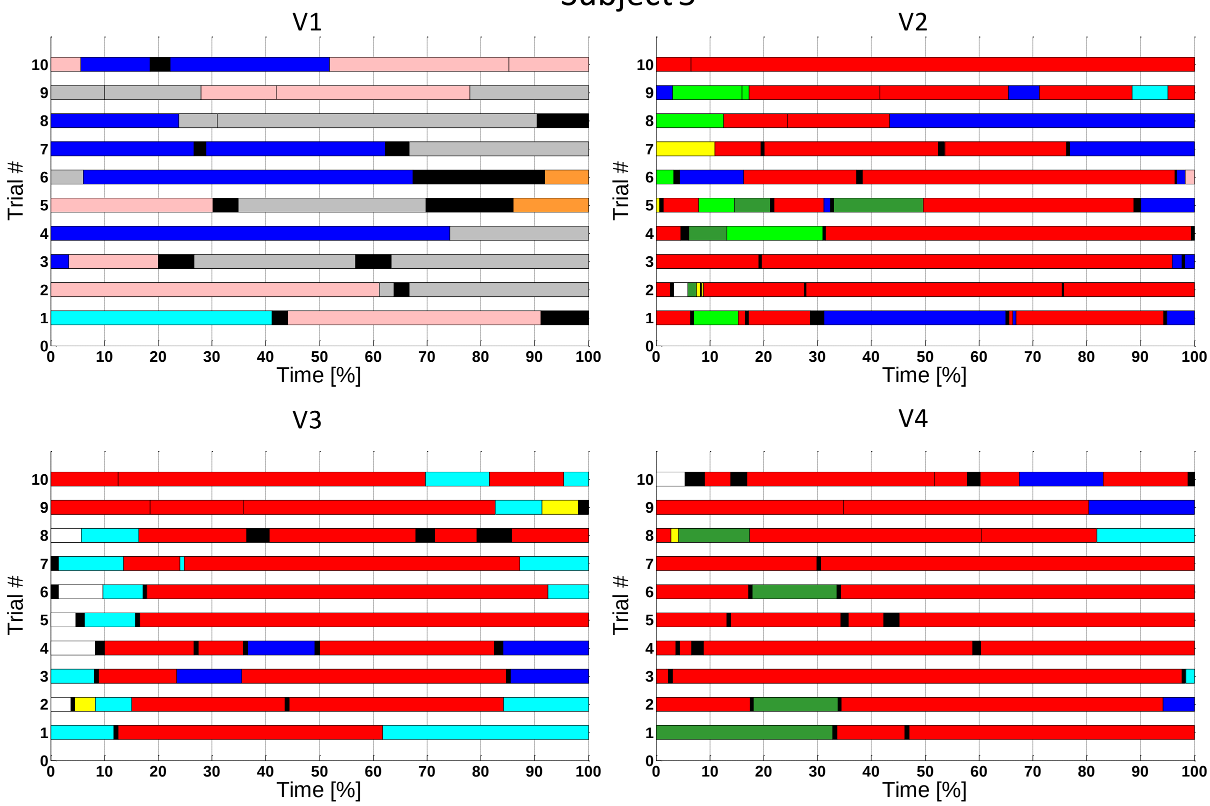
## Subject 3



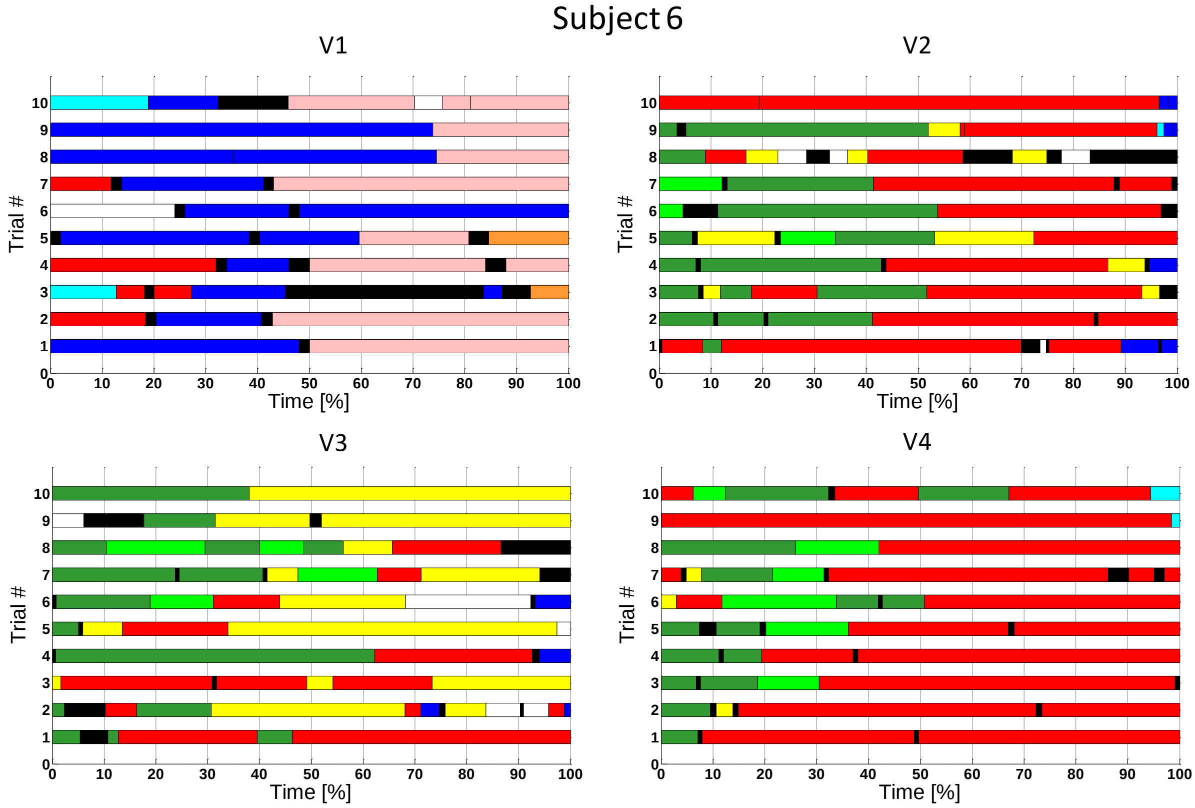

## Subject 4

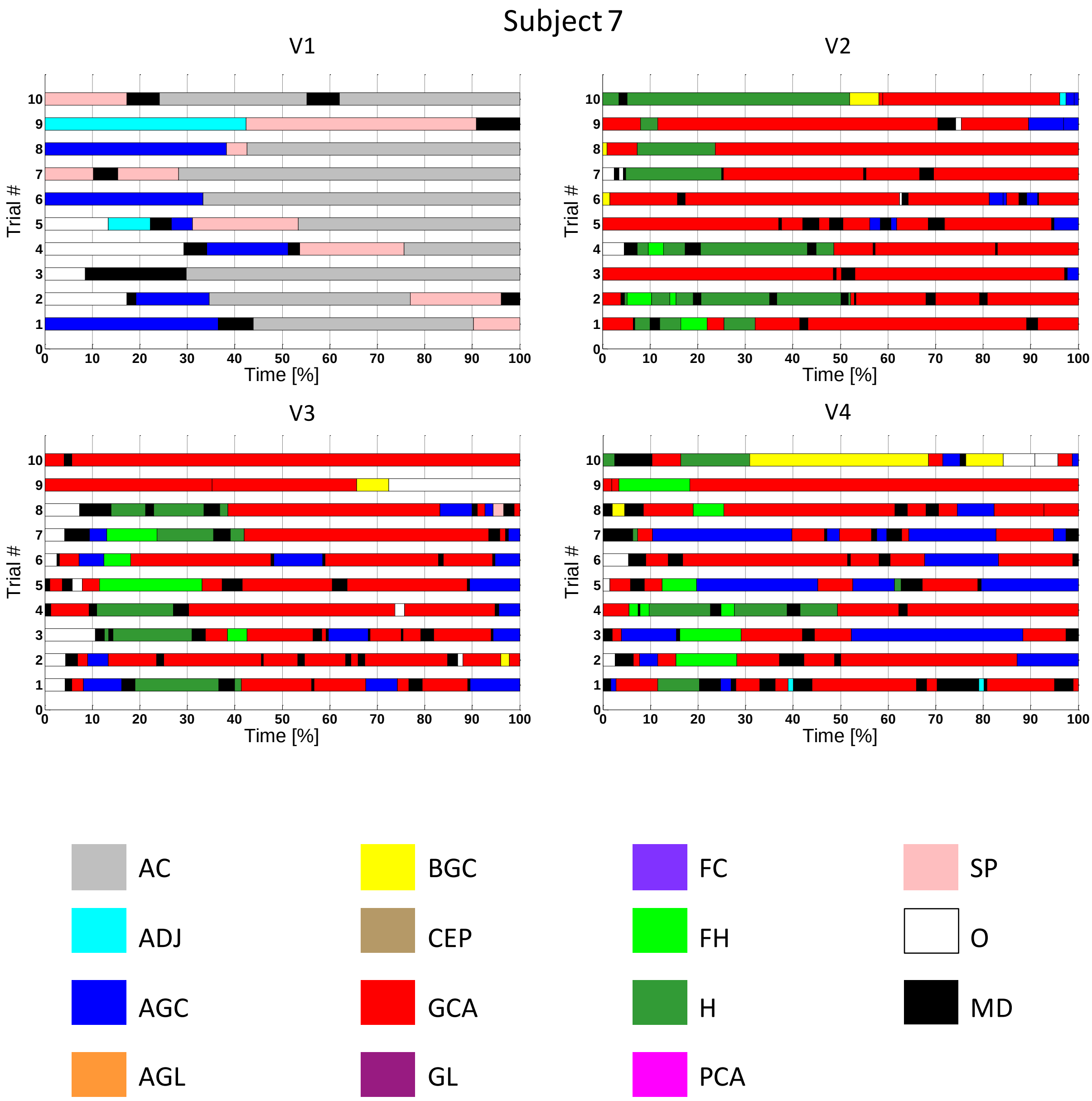


Subject 5



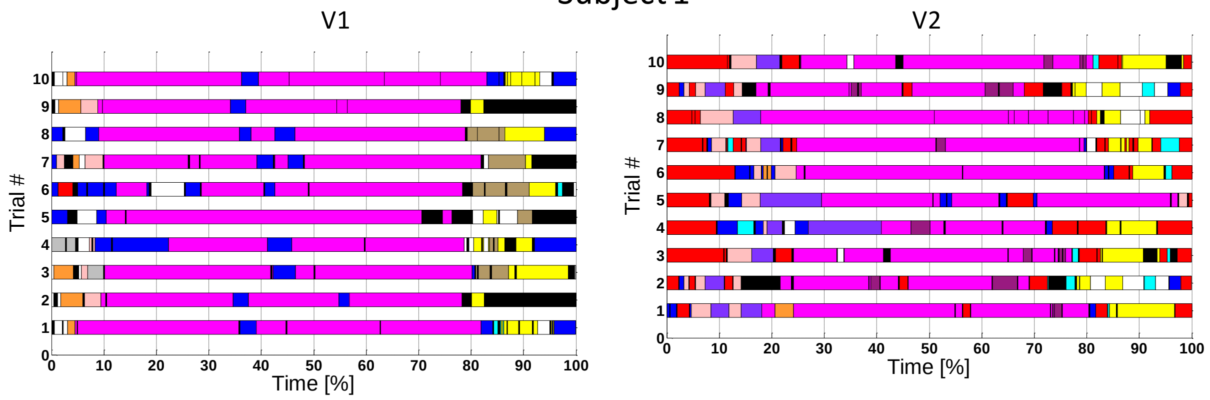

Subject 6



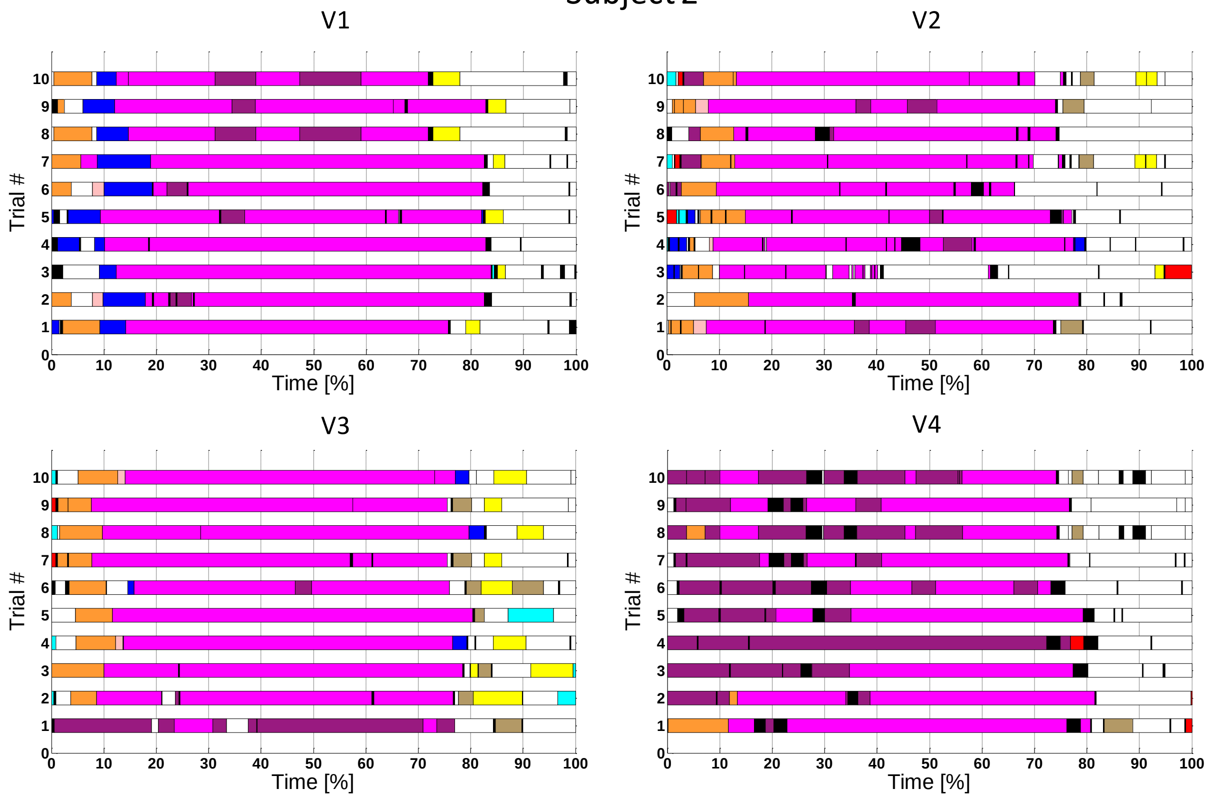

Subject 7
V1
V2
V3
V4
Trial #
Time [%]
0 10 20 30 40 50 60 70 80 90 100
AC
BGC
FC
SP
ADJ
CEP
FH
O
AGC
GCA
H
MD
AGL
GL
PCA

## I.2. Manipulation phase

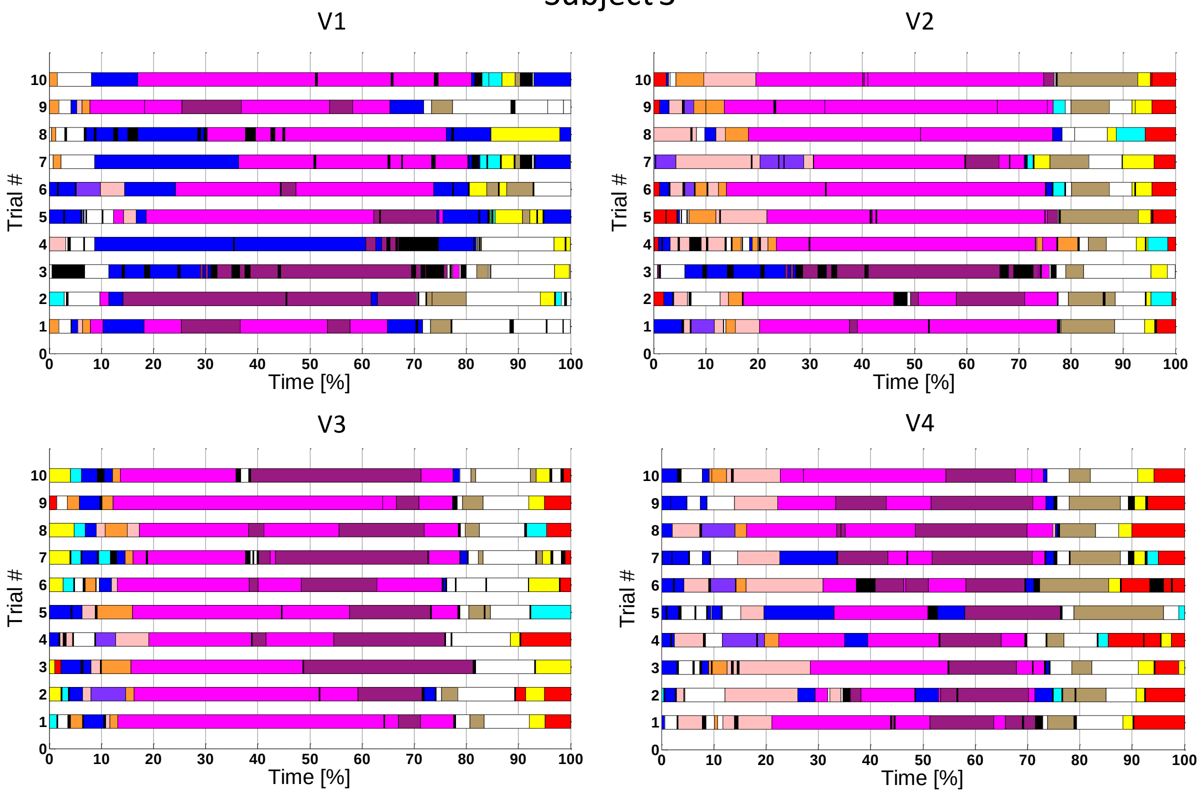
Subject 1



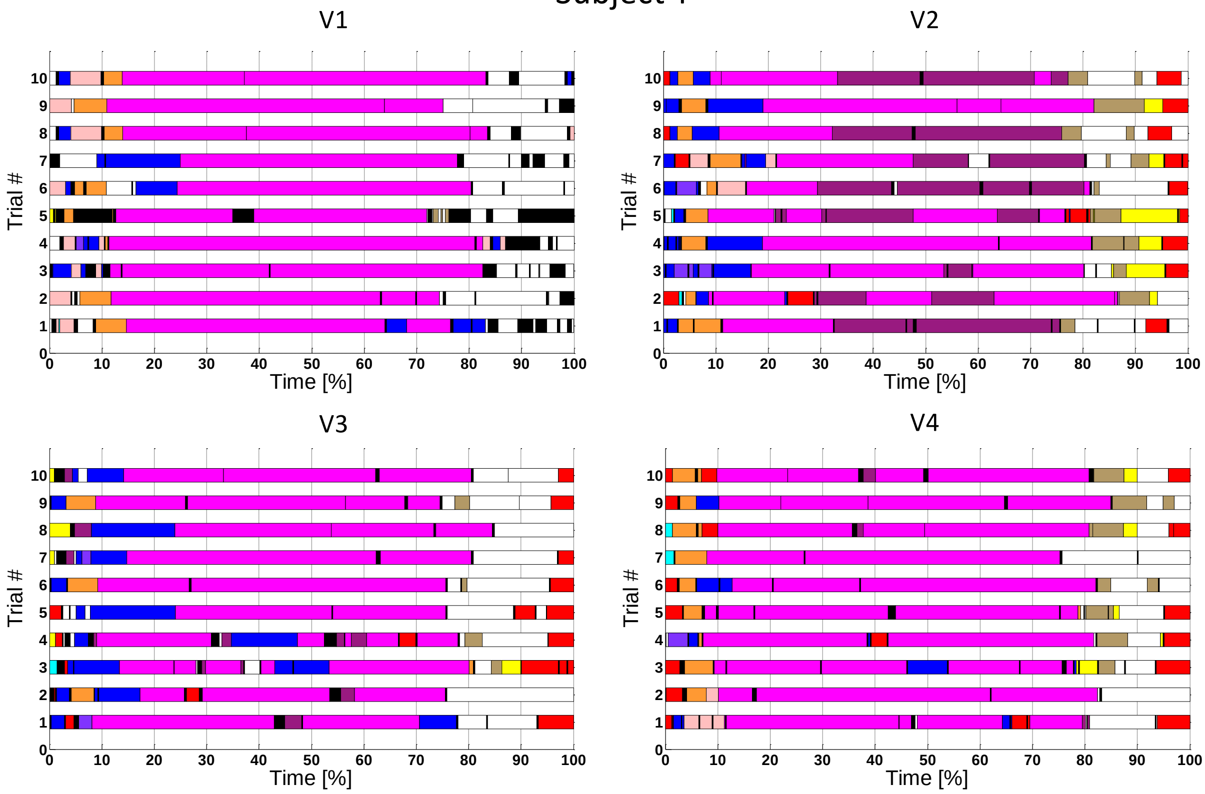

Subject 2



## Subject 3




## Subject 4



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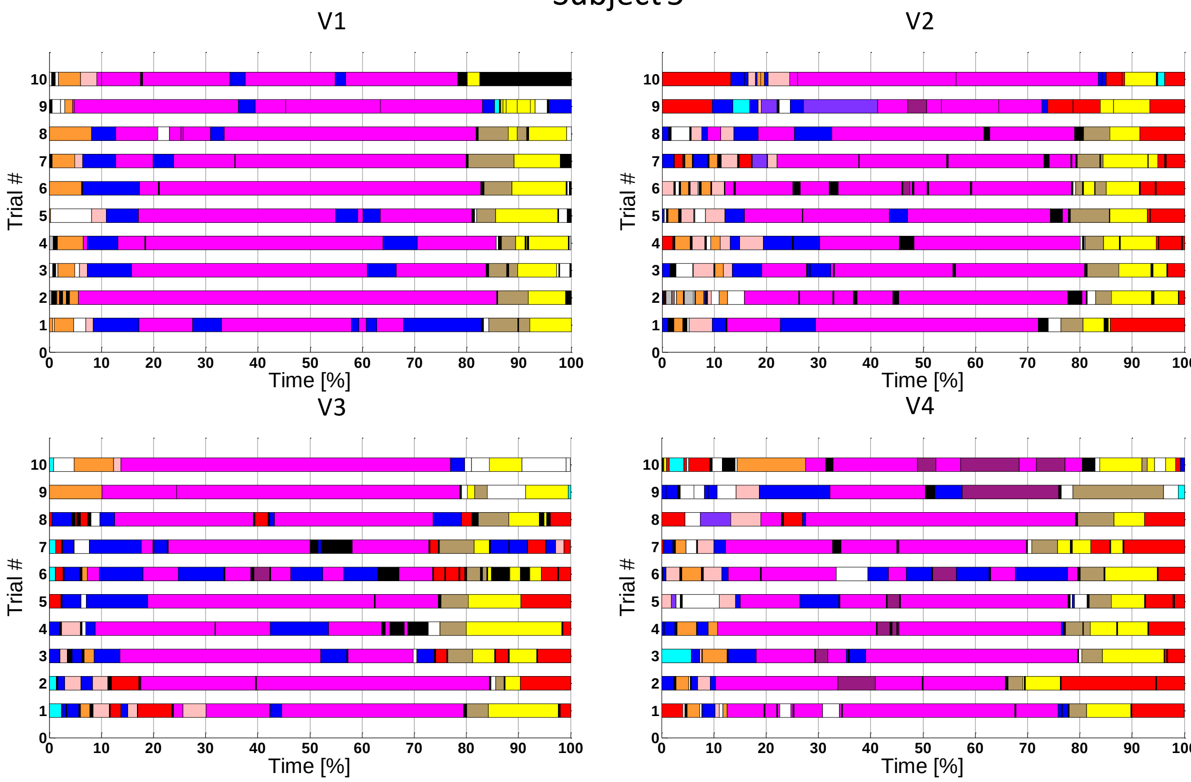
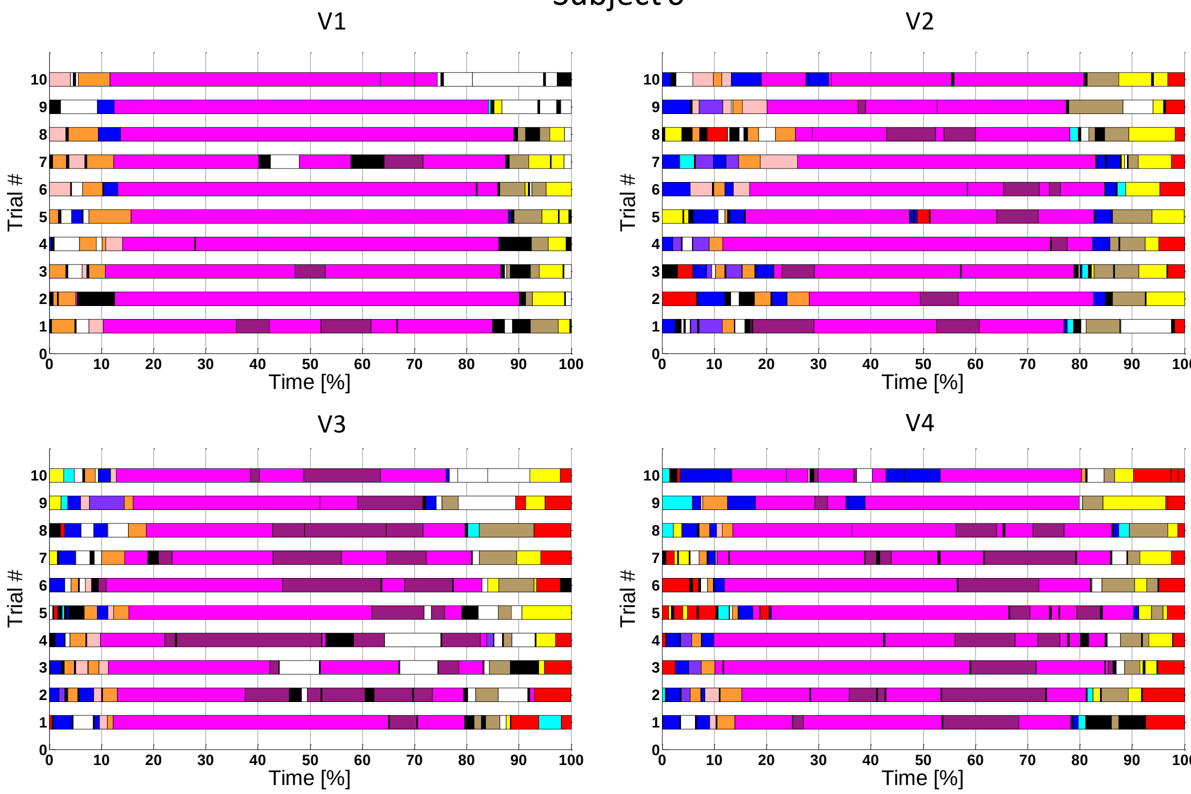
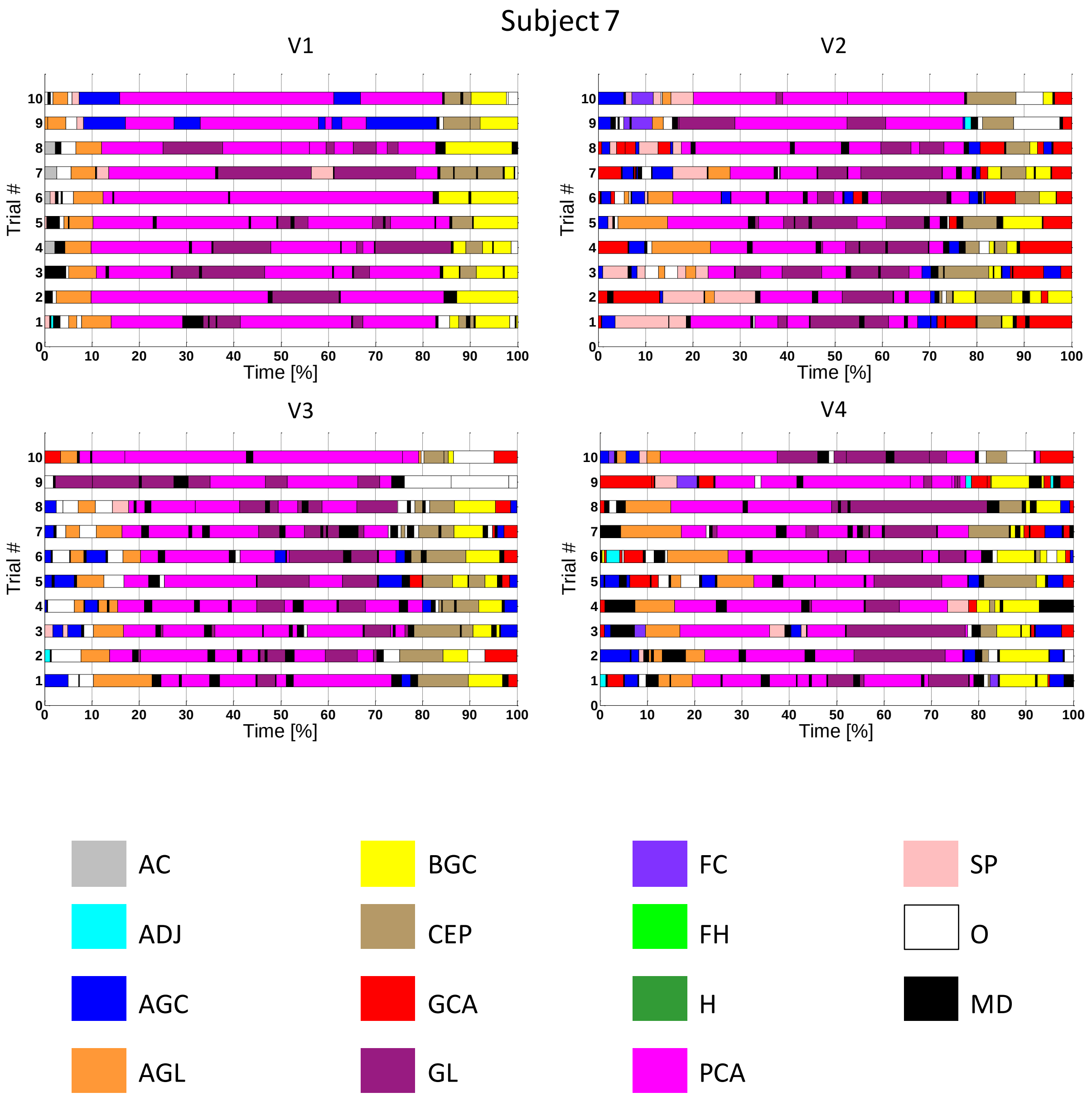



# Subject 6




Subject 7
V1
V2
V3
V4
Trial #
Time [%]
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1
2
3
4
5
6
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50
60
70
80
90
100
AC
ADJ
AGC
AGL
BGC
CEP
GCA
GL
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FH
H
PCA
SP
O
MD

**Appendix J: The Upper Extremity Functional Status of OPUS questionnaire**

# UPPER EXTREMITY FUNCTIONAL STATUS

| I. Do you use any assistive devices? (Check all that apply) | | II. Please indicate your affected limb(s). | | |
|---|---|---|---|---|
| ☐ Walker<br>☐ Auxiliary crutches<br>☐ Forearm crutches<br>☐ Wheelchair or scooter | ☐ One cane<br>☐ Two canes<br>☐ Other................. ........................... | ☐ Left arm | ☐ Right arm | ☐ Both arms |
| | | III. How many hours per day do you currently wear your prosthesis/ orthosis? ..................... hours/per day | | |

| IV. Using the scale to the right, please indicate how easily you perform the following activities. | 0. Not able<br>1. Difficult<br>2. Easy<br>3. Very easy | | | | V. Do you usually perform this activity using your prosthesis? | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | Using | Not Using |
| 20. Wash face | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 21. Put toothpaste on brush and brush teeth | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 22. Brush/comb hair | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 23. Put on and remove T-shirt | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 24. Button shirt with front buttons | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 25. Attach end of zipper and zip jacket | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 26. Put on socks | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 27. Tie shoe laces | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 28. Use fork or spoon | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 29. Pour from 12 oz can (340 ml) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 30. Write name legibly | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 31. Use scissors | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 32. Open door with knob | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 33. Carry laundry basket | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 34. Dial a touch tone phone | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 35. Fold a bath towel | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 36. Open an envelope | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 37. Stir a bowl | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 38. Put on and take off prosthesis | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Appendix K: Monitoring of Upper Limb Prosthesis Activity in Trans-Radial Amputees**[****]

There has been a shift in rehabilitation medicine from conventional evaluation procedures towards more quantitative approaches. However, up to now, a quantitative evaluation procedure for upper limb prostheses that is applicable outside of the laboratory or clinical environment has not been established. The requirement for such a procedure arises from the findings of a number of recent studies suggesting that unilateral trans-radial amputees do not involve their prosthesis in task performance in real life situations, even if they are able to demonstrate the use of the prosthesis in the clinical environment. This suggests that laboratory, or clinic-based assessments are limited in the information they provide to clinicians or designers of new prostheses. Further, self-report approaches, such as questionnaires or interviews rely on accurate recall and reporting by subjects, an approach that has been shown to be flawed in other rehabilitation and public health domains.

Therefore, this chapter reports a study investigating the feasibility of quantifying the nature and duration of tasks performed with a myoelectric prosthesis by means of an activity monitor. It was hypothesised that by monitoring the prosthesis hand opening and closing it may be possible to identify the manipulation phase. Such information could be used to segment acceleration signals, measured from arm-located accelerometers, which may contain information characterising the task(s) being performed and differentiate it/them from other tasks. The results of this study indicate that, by using a neural network classifier, customised for each user, acceleration signals measured during the manipulation phase of task performance could accurately characterise the task being performed. The implications of these findings and future work are discussed here.

[****] Abstract of Sobuh M, Kenney L, Tresadern P, Twiste M, Thies S. Monitoring of Upper Limb Prosthesis Activity in Trans-Radial Amputees. In: Murray C, (ed.). *Amputation, Prosthesis Use, and Phantom Limb Pain*. Springer New York. 2010. Most of this work was completed during the PhD candidates' MSc (by research) degree at the University of Salford, 2006-2008. However, the work was finalized and written up for publication during the first few months of the candidate's PhD, and therefore it is presented here.

## Appendix L: Poster presented at the BodyRep workshop, Goldsmiths, University of London, London, UK (2010)

University of Salford
A Greater Manchester University

# The role of visual attention in learning to use myoelectric prosthesis- A pilot study

M. Sobuh[1], L. Kenney[1], S. B. Thies[1], A. Galpin[2], P. Kyberd[3], M. Twiste[1]

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[3] Institute of Biomedical Engineering, University of New Brunswick, Canada

## Background

- Myoelectric prostheses are controlled from electrical signals generated during contraction of muscles in the residual limb.
- Many upper limb amputees face difficulties with using such devices in everyday life.
- Previous authors have proposed that this may be due to a high reliance on visual feedback for control, which may be reduced with training.

## *Objectives:*

- *Investigate the characteristics of visual attention during task performance with a myoelectric prosthetic hand.*
- *Compare these characteristics with those observed during the performance of the same task with the anatomical hand.*
- *Investigate the changes in visual attention during learning to use the prosthesis.*

## Methods

**Subject:** 1 anatomically intact subject.

**Task:** pouring water from a carton from a sitting position.

**Design:** Cross-over study.

- Two phases (Table 1):
  - *Phase1* (2 testing sessions: S1, S2), the anatomical hand used to complete the task.
  - *Phase 2* (3 testing sessions: S3-S5) a prosthesis simulator used to complete the task.
  - Upper limb functionality test (SHAP) also completed between sessions.

**Equipment:** Eye fixation measured using iView X HED 2 system™.

| Phase | Events | Tools |
|---|---|---|
| Phase 1 | Testing session 1 (S1): Task completion (10 times) | Eye-tracker |
| | Functionality evaluation | SHAP |
| | Testing session 2 (S2): Task completion (10 times) | Eye-tracker |
| | Functionality evaluation | SHAP |
| Phase 2 | Testing session 3 (S3): Task completion (10 times) | Eye-tracker |
| | Training and functionality evaluation | SHAP |
| | Training and functionality evaluation | SHAP |
| | Testing session 4 (S4): Task completion (10 times) | Eye-tracker |
| | Training and functionality evaluation | SHAP |
| | Training and functionality evaluation | SHAP |
| | Testing session 5 (S5): Task completion (10 times) | Eye-tracker |

**Table 1:** The experimental protocol.

**Data analysis:**

- Trials were segmented into reaching and manipulation phase prior to gaze analysis.
- Gaze events (fixation, saccade/blink) were identified for each trial during both reaching and manipulation phases.
- Fixation at the hand and grasping critical area on the carton (GCA) were identified during reaching phase.
- Fixation at the GCA was identified during manipulation phase.


**Fig 1:** Task performance (1: Task start/endpoint, 2: Reaching start point, 3: Reaching in progress, 4: Reaching endpoint/Manipulation phase start point, 5: Manipulation in progress, 6: Manipulation endpoint).

## Results

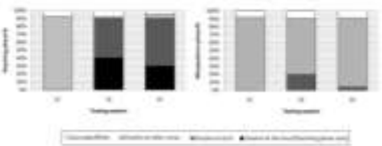

**Fig 2:** Averaged fixation.

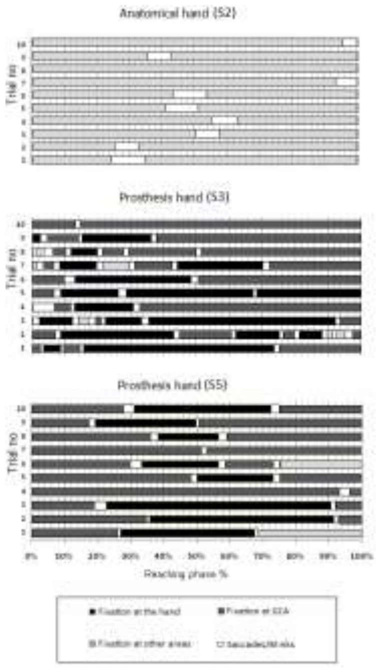


**Fig 3:** Fixation sequence during reaching phase.

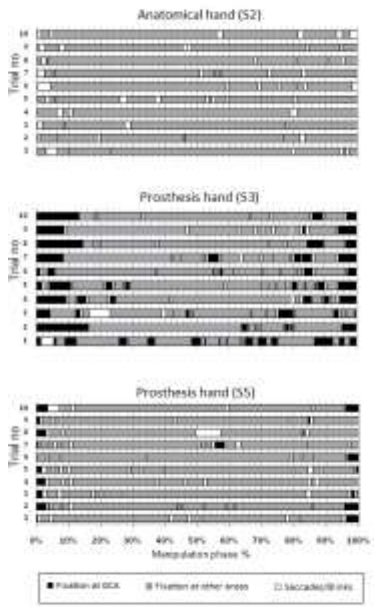


**Fig 4:** Fixation sequence during manipulation phase.

- Task completion time increased following introduction of prosthesis (8.8s in S2; 21.2s in S3), but decreased with training to 13.4s in S5.
- SHAP scores showed improvement with training (from 39% (S3) to 65% (S5) of healthy hand function).
- Eye fixation at the hand/ GCA seems to be a unique behaviour of prosthesis grasping and releasing.
- Fixation at GCA in manipulation decreased with training (from 20% (S3) to 3.75% (S5)).

## Conclusions

- As proposed by previous authors, prosthesis use requires a high degree of visual attention
- Visual attention during manipulation phase decreases with training.
- Further work to investigate the attentional demands of prosthesis use in amputee subjects.

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