Bimanual Coordination After Incomplete Cervical Spinal Cord Injury

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Abstract

This thesis examines unimanual and bimanual prehension in people with an incomplete cervical Spinal Cord Injury (icSCI) when compared to non-injured younger adults (YA) and older adults (OA). Quantifying control changes following icSCI will help to guide rehabilitation to improve arm and hand function, which is the main priority for rehabilitation following injury to the cervical spinal cord. Using 3D kinematic and surface EMG analysis, eighteen participants with an icSCI, sixteen YA and sixteen OA were examined, in three studies, when reaching and grasping objects, varying in distance and size, in unimanual and bimanual conditions. Kinematic data showed that participants with an icSCI produced unimanual and bimanual movements of a longer duration and lower peak velocity, with an increased reliance on the deceleration and final adjustment phase when compared to non-injured participants. With regards to the grasp phase, participants with an icSCI produced maximum grasp aperture earlier in the movement and with temporal dissociation between the transport and grasp phases. Participants with an icSCI also showed novel muscle activity patterns when compared to non-injured participants, suggesting that neuroplasticity of spared fibres had occurred in the acute stages of the injury. Object distance and object size influenced both the transport and grasp phases of unimanual and bimanual prehension, resulting in control differences between participants with an icSCI and non-injured participants e.g. longer movement time and increased reliance on the final adjustment phase when reaching to large objects. Despite bilateral deficits of the arms and hands, participants with an icSCI showed evidence for retaining a level of bimanual coordination, such as using the final adjustment phase to improve synchrony between the limbs. This supports the integration of bimanual movements into rehabilitation in order to improve arm and hand function, as well as the performance of activities of daily living, which are often bimanual in nature.

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Overview of research aims

This thesis came about due to the author's interest in upper limb function following incomplete cervical spinal cord injury (icSCI) and how this differs to non-injured individuals. Despite regaining arm and hand function being the main priority for rehabilitation following injury to the cervical spinal cord (Anderson, 2004, Snoek et al., 2004), there has been limited research focusing on the control of upper limb movements, when compared to literature based on lower limb function and other clinical populations such as stroke. Reaching and grasping is a fundamental task of daily living and has been widely researched in non-injured adults and the stroke population, as it helps to understand how the nervous system controls and coordinates multi-joint actions (shoulder, elbow and hand) (Wang and Stelmach, 2001).

The use of kinematic and surface electromyography analysis to investigate reaching and grasping allows for detailed analysis of upper limb control (e.g. movement time, number of adjustments and muscle activity patterns), when compared to clinical and functional tests (de los Reyes-Guzman et al., 2010, Jacquier-Bret et al., 2008, Jacquier-Bret et al., 2009), and is therefore the focus within this thesis. Additionally, throughout this thesis the focus is on individuals with an icSCI, as it is reasonable to assume that there are spared sensorimotor pathways that can be accessed and used to facilitate functional recovery of the arm and hand (Raineteau and Schwab, 2001, Marsh et al., 2011).

The unimanual research undertaken to date shows that individuals with a cervical SCI (cSCI) produce movements with a longer movement time, lower peak velocity and prolonged deceleration phase when compared to non-injured participants (Mateo et al., 2015). It has also been suggested that due to paralysis of muscles of the upper limbs novel muscle activity patterns are utilised in order to complete the reach to grasp movement (Koshland et al., 2005, Janssen-Potten et al., 2008, Jacquier-Bret et al., 2009).

In non-injured individuals the effects of object size and object distance have been used to obtain a greater understanding of upper limb control (e.g. how increasing object distance and size influence kinematic parameters and muscle activation), however, there is limited research that takes this approach in the cSCI population. Therefore, the first study took the form of two experiments (object distance and object size) with the aim to quantify how unimanual prehension changes after icSCI when compared to non-injured younger adults (YA) and older adults (OA).

Throughout the thesis the latter was considered important due to the aging SCI population (Thompson et al., 2014), and the differences from YA already highlighted from previous prehension studies (Seidler-Dobrin and Stelmach, 1998, Goggin and Stelmach, 1990, Coats and Wann, 2011).

Despite most activities of daily living being bimanual in nature, therapy after cSCI generally focuses on improving unimanual function of the more impaired limb (Hoffman and Field-Fote, 2007). Having said this, pilot research in the cSCI population has supported the use of bimanual therapy for improving bimanual upper limb function, and highlighted the task specific training needed to induce these improvements (no bimanual improvement seen after unimanual training) (Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2010, Hoffman and Field-Fote, 2013). However, to date there has been no one study that has quantified how the upper limbs are controlled bimanually, despite bimanual deficits shown after cSCI (Cacho et al., 2011), which will help to guide rehabilitation Therefore, the second study within this thesis aimed to examine bimanual prehension following icSCI and how this differed to non-injured YA and OA. It took the form of two experiments (object distance and object size) in order to investigate how symmetric and asymmetric bimanual conditions influenced bimanual coordination. Finally, in order to provide further understanding of bimanual control after icSCI, the third study aimed to compare unimanual and symmetrical bimanual prehensile actions in individuals icSCI, and how this differed to YA and OA.

Chapter 1 Overview of Spinal Cord Injury

1.1 Introduction

Spinal Cord Injury (SCI) is defined as the disruption of nerve fibres which convey ascending sensory and descending motor information, resulting in sensorimotor and autonomic dysfunction below the level of the lesion (Raineteau and Schwab, 2001). This chapter details the prevalence, causes and effects of a SCI as well as potential mechanisms of recovery. Finally, this chapter addresses the current rehabilitation paradigms that are prevalent in the SCI population.

1.2 Incidence of Spinal Cord Injuries

Quantifying the incidence rate of SCI's worldwide proves a difficult task as some countries do not have a SCI register, including the UK. Additionally, even in those countries with a SCI register, the number of SCI's reported is largely variable between studies, as some registers take into account those admitted to a Spinal Injuries Centres, whilst others also include those admitted to a general hospital. Overall the global incidence rate is estimated at 23 traumatic spinal cord injury (see 1.3.1) cases per million people, which equates to 179,312 cases per year (Lee et al., 2014). The cost to healthcare systems is not just in the first stages following SCI but continues in the long term as home care is required and secondary problems, such as pressure sores, occur (Wyndaele and Wyndaele, 2006). This cost is also on the increase due to the rising life expectancy of people with a SCI and the increasing age (13 year increase from 2000 to 2011) of those people suffering a SCI who may already have long term medical conditions that need managing e.g. diabetes or heart problems (Thompson et al., 2014).

1.3 Characterisation of Spinal Cord Injuries

To characterise a SCI it is important to know the cause, skeletal level and severity of the SCI, i.e. the amount of damage to the spinal cord.

1.3.1 Causes of Spinal Cord Injury

The causes of SCI are categorised into traumatic and non-traumatic. Generally traumatic SCI's are the most common (Chen et al., 2013) with road traffic accidents and falls (particularly in Western Europe where the population is aging) being the greatest cause (Lee et al., 2014). The most common causes of non-traumatic SCI's include Spinal Stenosis (compression of the spinal cord) and Spinal tumours, which are generally associated with an aging population (McKinley et al., 1999). In this thesis, both traumatic and non-traumatic causes of SCI will be included within the participants demographic to increase participant recruitment.

1.3.2 Skeletal level of the Spinal Cord Injury

The spinal cord extends through the vertebral canal and is approximately 42-43cm in females and 45cm in males (Watson et al., 2009) terminating between vertebral levels L1 and L2 (in the lumbar segments of the spinal cord) in adults (Crossman and Neary, 2010). Spinal nerves transmit sensory information from the target to the central nervous system and send motor commands from the central nervous system to the target muscles or organs (Crossman and Neary, 2010). A SCI to the upper, cervical segments of the spinal cord (neck) results in paralysis of all four limbs and trunk. A SCI to the lower, thoracic, lumbar and sacral segments of the spinal cord results in loss of function of the lower limbs (Maynard Jr et al., 1997). Injury to the cervical spinal cord is more common than injury to the lower segments of the spinal cord, thus Tetraplegia is more common than Paraplegia (Thompson et al., 2014, Marino et al., 1999). It is also important to note that Tetraplegics rate regaining arm and hand function as their main priority for rehabilitation when compared to any other function, e.g. regaining the ability to walk, in order to improve their functional independence and overall quality of life (Anderson, 2004, Snoek et al., 2004). This thesis focuses on arm and hand function following SCI therefore the participants recruited had sustained a SCI to the cervical segments of the spinal cord (cSCI). In humans, the cervical spinal cord is split into eight segments (C1-C8) and a cSCI at the level cervical 8 (C8) results in dysfunction of the flexor digitorum superficialis (finger flexors), C7 results in dysfunction of the triceps brachii (elbow extensors), C6 results in dysfunction of the extensor carpi radialis (wrist extensors) and C5 results in dysfunction of the biceps brachii (elbow flexors), with each level adding dysfunction to more muscles.

1.3.3 Severity of the Spinal Cord Injury

Depending on the amount of damage to the spinal cord a SCI can be complete or incomplete (iSCI). However, in humans a complete SCI is almost never anatomically complete and thus some functional recovery is possible (Beekhuizen and Field-Fote, 2005, Marsh et al., 2011, Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2013). Individuals with an incomplete cervical spinal cord injury (icSCI) have been shown to regain greater muscle strength in the biceps brachii, extensor carpi radialis and triceps brachii when compared to those with a complete cervical SCI (Ditunno et al., 2000) and this was in the acute (< 1 year) and chronic (>1 year) stages of SCI (Curt et al., 1998). Generally, it is accepted that greater functional recovery is seen after icSCI (see section 1.4) as it is reasonable to assume that there are some spared ascending and descending pathways that can be accessed during rehabilitation and give rise to functional recovery likely due to neuroplasticity (Raineteau and Schwab, 2001, Backus, 2008, Marsh et al., 2011).

The globally used measure to determine the severity of SCI is the American Spinal Injury Association (ASIA) classification (Table 1.0). This classification system takes into account both motor and sensory scores of muscles and skin dermatomes. ASIA motor scores are determined by assessing the strength of key muscles bilaterally using the manual muscle test, which rates force generation on a scale of 0 to 5 (0=no palpable or visible muscle contraction, 5=holds muscle contraction against maximal resistance) (Field-Fote, 2009). The sensory score is determined by measuring the perception of bilateral dermatomes of the skin to light touch and pin prick. The most rostral dermatome to have sensation for both the perception of light touch and pin prick is then defined as the sensory level. The final assessment for the ASIA classification is the voluntary contraction and sensation of the anal sphincter (S4-5), which determines whether the injury is classed as incomplete or complete. Studies have reported good psychometric properties of the ASIA classification including good inter-rater reliability (Savic et al., 2007) and predictive validity (Blaustein et al., 1993). In terms of recovery it has been shown that greater motor recovery is seen in people classified as ASIA D and least seen in ASIA A (Marino et al., 1999), which is expected as ASIA A indicates a complete SCI. The participants in this thesis ranged in ASIA classification from B-D confirming that the SCI was incomplete, but they had some sensorimotor dysfunction.

1.4 Recovery following incomplete cervical Spinal Cord Injury

Due to impairment of arm and hand function following cSCI, it is not surprising that Tetraplegics rate regaining arm and hand function as their greatest priority for rehabilitation (Anderson, 2004), stating that this would improve their quality of life most of all compared to regaining any other function such as walking or bladder function (Snoek et al., 2004). Recovery of function, e.g. performance of activities of daily living, has been related to the amount of neuroplasticity (see 1.4.1) following SCI. This is because greater improvements in function due to neuroplasticity has been found following iSCI compared to complete SCI (Curt et al., 2008). Neuroplasticity is defined as the adaptive changes (including maladaptive) that occur within spared neural circuitries and therefore reflects reorganisation of the nervous system following injury (Dietz and Fouad, 2014).

Table 1.0: The ASIA classification system.

ASIA classification	Description
A	No sensory or motor function is preserved in sacral segments S4- S5.
B	Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S5.
C	Motor function is preserved below the neurological level, and more than half of the key muscles below the neurological level have a muscle grade less than 3.
D	Motor function is preserved below the neurological level, and at least half of the key muscles below the neurological level have a muscle grade greater than or equal to 3.
E	Sensory and motor function is normal.

1.4.1 Neuroplasticity

Following iSCI, neuroplasticity may occur via two levels: in pre-existing circuits e.g. synaptic modifications, or by the appearance of new circuits e.g. sprouting of axons, and these mechanisms are better understood using animal models (Raineteau and Schwab, 2001). Spared fibres following iSCI can sustain a high level of functional recovery with as little as 10% of fibres spared by a spinal lesion being sufficient enough to regain unsupported walking in cats (Windle et al., 1958). The sprouting of neuronal fibres and changes in synaptic plasticity can occur at different levels of the motor system, including the motor cortex, brainstem, descending spinal tracts and interneurons of the spinal cord. This poses difficulty in understanding the exact mechanisms of plasticity and subsequent functional recovery refined by activity-dependent training (Raineteau and Schwab, 2001). Spontaneous recovery of spared fibres following iSCI does occur within the first few months after a SCI (Curt et al., 2008), but nevertheless is often fragmentary and this becomes evident when attempts at complex tasks occur (Raineteau and Schwab, 2001, Krajacic et al., 2010). Additionally, following training interventions in rodents, performance of untrained tasks has been shown to deteriorate (Krajacic et al., 2010), which suggests that different training interventions, e.g. paw reaching and ladder walking, cause interference as the motor tasks/skills compete for spared neuronal circuits (Weishaupt et al., 2013b, Weishaupt et al., 2012). The majority of the recovery of sensorimotor deficits occurs in the first 12-15 weeks following SCI (Curt et al., 2008), however, following this time period, training induced changes can still occur, highlighting the importance of rehabilitation paradigms (Dietz and Fouad, 2014). Age has been shown to limit plasticity and subsequent restoration of function as older adults have greater problems with translating neural recovery into improvements of activities of daily living (Jakob et al., 2009). This has implications to the current SCI population as those sustaining a SCI are increasing in age (Thompson et al., 2014).

1.4.2 The Corticospinal Tract

The CST originates from cortical areas, such as the primary motor cortex and supplementary motor area, and terminates within the spinal grey matter (ventral horn and dorsal horn), highlighting its multifunctional nature in motor and sensory functioning (Lemon, 2008). The CST is separated into two columns as 75-90% decussates to form the contralateral CST and 10-25% remains ipsilateral to form the ipsilateral CST (Crossman and Neary, 2010). CST projections originating from the primary motor cortex are of great importance for producing voluntary movements, those from dorsal and ventral premotor areas are involved in the sensory guidance of movements, and those from the supplementary motor area are involved in the planning and coordination of movement sequences (Lemon and Griffiths, 2005; Lemon, 2008). CST projections to the dorsal horn postulate that the CST is involved in modulating sensory function, such as proprioception (Lemon and Griffiths, 2005), however, these projections are less pronounced than the projections to the ventral intermediate zone of the spinal grey matter suggesting greater involvement in motor control (Lemon, 2008). Therefore if a lesion, such as a spinal cord injury, is sustained to the CST there is deterioration in sensorimotor control (Lemon and Griffiths, 2005). To fully understand the role of the CST research is primarily based on primate models due to their similarity to human descending pathways, however, the effects of training interventions are largely focused on rodent models (Lemon and Griffiths, 2005).

A study in rodents has shown that a training intervention (forepaw reaching), following cSCI, induced axonal sprouting of the spared fibres of the CST and this induced increases in forepaw reaching function (the trained task), but no improvement in the untrained task (horizontal ladder walking) (Krajacic et al., 2010). This highlights the task specific nature of functional recovery and neural plasticity of the CST, but also that new/alternative connections offer a promising substrate for recovery.

In primates the CST has been found to have vast bilateral projections, which could be a potential pathway for recovery following injury to the CST via sprouting of spared axons to nearby denervated areas of the spinal cord (Rosenzweig et al., 2009). Rosenzweig and colleagues conducted a study to assess the spontaneous plasticity (sprouting) of CST projections and subsequent upper limb recovery after cSCI in macaque monkeys (Rosenzweig et al., 2010). Fourteen macaque monkeys were trained on a fine motor control task (food retrieval from a flat surface) and were then split into intact animals and those who received a C7 hemisection SCI. Axonal tracing and performance of the food retrieval task as well as EMG of forelimb muscles were used to track recovery following the C7 hemisection. The results showed that spontaneous plasticity of CST axons in the lesioned spinal cord occurred, as axon density was restored to 60% of the level in intact animals. This 60% restoration of axon density was also coupled with improvements in hand function, supporting the role of the CST in recovery.

A body of research has also investigated the combination of training interventions with therapeutic interventions on CST plasticity in rodents (Wang et al., 2011, Weishaupt et al., 2012, Maier et al., 2009). The use of the enzyme Chondroitinase ABC (ChABC) and task specific rehabilitation (paw reaching) promoted axonal sprouting of the CST to enhance the results of rehabilitation following chronic SCI. The suggested mechanisms of this enhancement include reconnection of spared CST fibres from above the lesion to interneurons within the spinal cord that project below the lesion (Wang et al., 2011). However, studies using different therapeutic interventions (Brain Derived Neurotrophic Factor and Anti-NOGO-A antibody) have found that the gains in function were not due to reorganisation of the CST (Weishaupt et al., 2012, Maier et al., 2009) suggesting that other descending pathways may contribute to training-induced recovery. This highlights the complex, multifaceted nature of neuroplasticity and recovery following SCI.

1.4.3 The Reticulospinal Tract

Recent research has concluded that corticospinal plasticity alone may not fully explain the recovery of function following training interventions in rodents (Krajacic et al., 2010). Other than the CST another descending pathway, named the reticulospinal tract (RST), has also been suggested to influence voluntary upper limb movements in primates (Baker, 2011, Riddle et al., 2009) and could provide an additional substrate for recovery of function. The RST arises from the pons and medulla and descends ipsilaterally to control voluntary actions, as well as reflex actions and muscle tone (Crossman and Neary, 2010).

The RST has shown the ability to sprout and rewire following injury to the thoracic spinal cord in rodents (Ballermann and Fouad, 2006). Additionally, after cervical SCI (C4, disruption to the CST), the RST showed signs of neuroplasticity, e.g. increased fibre density, and subsequent improvement in function (e.g. pellet reaching). However, this neuroplasticity was minor above the injury (Weishaupt et al., 2013a, Ballermann and Fouad, 2006). In addition, a loss of RST projections below the injury after cervical SCI was observed, and this finding warrants further study into mechanisms of RST plasticity, such as changes at the synaptic level (Weishaupt et al., 2013a).

1.5 Rehabilitation following cervical Spinal Cord Injury

The mechanisms of recovery are best understood using animal models, as above. However, a body of research has focused on the cortical changes (parts of the brain that control movement) following SCI and functional gains following rehabilitation in human participants, which is also a form of neuroplasticity outside of the spinal cord. This section addresses the interventions currently being researched.

1.5.1 Cortical reorganisation following Spinal Cord Injury

Evidence in the literature has suggested that the loss of arm and hand function following a cSCI and subsequent cortical reorganisation is similar to that following a stroke (Field-Fote, 2009). Although the mechanisms of injury are different in cSCI and stroke (trauma versus ischemia), the similarities in cortical reorganisation suggest that rehabilitative strategies used in the stroke population may translate to the cSCI population (Iseli et al., 1999). Further to this, neuroplasticity underpins the recovery of sensorimotor function following cSCI and stroke (Dietz and Fouad, 2014).

The cortical reorganisation begins with the phenomenon known as learned non-use of the more affected limb. As the more affected limb begins to make failed attempts at movements of the upper limb, such as grasping, the individual is less likely to continue attempting to use the more affected limb. This non-use prompts cortical reorganisation in the ‘use it or lose it’ context as other used regions of the motor cortex begin to overtake that of the unused muscles (Nudo et al., 1996). In addition to this reduction in size of the cortical representation, there is also a posterior shift of this cortical area (Green et al., 1998, Green et al., 1999). This suggests that people with a SCI rely more heavily on the somatosensory cortex as opposed to the motor cortex when controlling voluntary movement (Green et al., 1998), which is reversed as recovery of hand function emerges (Green et al., 1999). Reorganisation of the areas within the somatosensory cortex also takes place as other areas with increased sensory input and voluntary movements take over e.g. the face (Jain et al., 1998). The decrease in voluntary movement of the more affected limb and underlying damage to the ascending and descending pathways within the spinal cord also causes a decrease in motor cortex excitability (Field-Fote, 2009, Freund et al., 2011). This has been identified using transcranial magnetic stimulation (TMS), a tool used to non-invasively measure cortical reorganisation and has shown that the greater spinal cord atrophy, i.e. more severe the lesion, the greater the reduction in excitability and increase in inhibition within the motor cortex (Freund et al., 2011). The use of unimanual and bimanual training interventions have been shown to improve arm and hand function by reversing changes in cortical reorganisation following cSCI (Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2010) and are addressed below.

1.5.2 Unimanual massed practice training

Unimanual massed practice training involves repetitive performance of simple tasks and has been shown to improve arm and hand function following stroke and induce changes in cortical reorganisation (Wolf et al., 1989, Taub and Morris, 2001, Liepert et al., 2000). Additionally, the use of somatosensory stimulation (stimulation of peripheral nerves) has been showed to improve cortical excitability and improve arm and hand function in the form of pinch strength following stroke (Conforto et al., 2002, Kaelin-Lang et al., 2002). From these findings the development of studies focused on the effects of unimanual massed practice in individuals with a cSCI have emerged. In the chronic icSCI population, unimanual massed practice [tasks included; grip (holding a hammer), grip with rotation (opening a jar), pinch (picking up small objects e.g. paperclips), pinch with rotation (putting nuts on bolts) and gross motor movements (throwing a dart)] in combination with somatosensory stimulation (of the median nerve) has been shown to induce greater improvements in arm and hand function (pinch strength and functional tests) compared to unimanual massed practice alone (Beekhuizen and Field-Fote, 2005). The additional gains in strength and function with somatosensory stimulation may be due to increased sensory input and cortical reorganisation (posterior shift) as the somatosensory cortex becomes involved with arm and hand motor function (Green et al., 1998, Green et al., 1999).

1.5.3 Bimanual massed practice training

Since most activities of daily living (ADL) require the use of both hands simultaneously, the task specific nature of neuroplasticity (Krajacic et al., 2010) and the bilateral deficits seen following cSCI; there has been emergence of research looking at the benefits of bimanual massed practice on arm and hand function after cSCI (Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2010, Hoffman and Field-Fote, 2013). This also translates to the aging population of those sustaining a SCI (Thompson et al., 2014) as it has been suggested that older adults find the translation of recovery into performance of activities of daily living problematic, and would therefore benefit from the focus on activities of daily living in bimanual massed practice (Dietz and Fouad, 2014). Bimanual massed practice is more widely used in the stroke population and has been shown to improve spatiotemporal (e.g. movement time) control of the more affected limb as well as improve scores on functional tests when compared to standard unimanual therapy (Lin et al., 2010). The mechanisms of improved function following bimanual therapy include the need to control more muscles and joints (greater number of degrees of freedom) (Bernstein, 1967), which subsequently increases cortical activity as the two limbs are activated (Sadato et al., 1997). Additionally, bimanual movements increase cortical excitability and elicit a greater muscle response (motor output) as the contralateral homologous muscle is also contracted simultaneously, known as cross facilitation (Hess et al., 1987, Stinear et al., 2001). The principle of cross facilitation has been suggested to be of potential benefit to people with a cSCI to facilitate optimal motor output (Jankowska et al., 2005).

Early pilot research in a case study (C6 chronic, complete injury) showed that bimanual therapy (tasks included grasp e.g. building lego, grasp with rotation e.g. can opener, pinch e.g. threading a needle, pinch with rotation e.g. key and padlock, and finger isolation e.g. typing on a keyboard) in combination with somatosensory stimulation of the median nerve led to improvements in strength, functional ability (unimanual and bimanual) and sensory function (perception of touch) (Hoffman and Field-Fote, 2007). Additionally, TMS was used to map cortical reorganisation and showed that, following the bimanual training paradigm, the biceps brachii cortical motor map showed an anterior shift and increased in area and volume. Therefore, cortical reorganisation to normal excitability and levels of activation occurred and was associated with increases in functional ability. In a subsequent study the effects of unimanual versus bimanual massed practice training following chronic cSCI (above C8) were investigated (Hoffman and Field-Fote, 2010). The results showed that bimanual training improved both unimanual and bimanual upper limb function, but only those who undertook the bimanual training improved their scores on the bimanual functional test (Chedoke Arm and Hand Inventory). Although this may seem self-explanatory, it highlights that bimanual movements and coordination between the limbs do not arise by training unimanual movements and must be specifically trained. The final example of research that focuses on bimanual training following chronic cSCI also highlighted that only the bimanual training group showed improvements in bimanual upper limb function, providing further support for task specificity during rehabilitation (Hoffman and Field-Fote, 2013).

1.6 Conclusion

SCI is more often caused by traumatic causes such as motor accidents and falls, and iSCI's are more common than complete SCI's. Following iSCI nerve fibres are spared and can be accessed by therapeutic and rehabilitation interventions to improve function. The neuroplasticity of these fibres is still not fully understood and ongoing research in animal models is being undertaken to explain the possible mechanisms that lead to improved function. New pilot data have suggested that bimanual therapy may be a successful rehabilitation intervention following injury to the cervical spinal cord. However, more research to understand the underlying control strategies of unimanual and bimanual movements and bimanual deficits following icSCI is needed in order to design appropriate rehabilitation interventions, forming the basis of the current thesis. In non-injured individuals behavioural studies focusing on precision grip (grip between the index finger and thumb) tasks are often used to investigate the control of unimanual and bimanual movement. The following chapter will address the neurological control of the precision grip and the importance of spinal structures.

Chapter 2 Control of the precision grip and bimanual movements

2.1 Introduction

The current chapter covers control of the precision grip (grip between the index finger and thumb) at a spinal level, which is highly relevant to the task chosen for this thesis. The role of corticospinal tract (CST), spinal interneurons, propriospinal neurons and reticulospinal tract (RST) are discussed. Finally, the role of the corticospinal tract in the control of bimanual movements is addressed.

2.2 Importance of the Corticospinal Tract in the control of the precision grip

Early research indicated that the CST has a specific role when completing prehensile movements with greater activity when producing the precision grip compared to palmar grasps, which require the use of the whole hand (Muir and Lemon, 1983). Muir and Lemon trained a monkey (using food rewards) firstly to squeeze two small springload levers using a precision grip of the left hand into a target position (displacing each lever by 3mm for 1.5 seconds) and to perform a power grip task, which required the monkey to grasp and squeeze an air-filled rubber cylinder with all four fingers and thumb (again maintaining the pressure for 1.5 seconds). After the training period electrodes were placed in the right motor cortex (surgical procedure) to allow identification of activity of the CST neurons during the task. Once recovered the monkey completed the tasks as activity of the CST neurons was recorded along with surface electromyography (EMG) of intrinsic hand muscles (first and second dorsal interossei and muscles of the palm (thenar eminence)) and forearm muscles (extensor digitorum superficialis, flexor digitorum superficialis, flexor pollicis longus, abductor pollicis longus) to determine the excitatory influence of the CST on the different muscles as the tasks were completed. The results revealed that despite the EMG activity of the intrinsic hand muscles being similarly active during the tasks the CST motor neurons were highly active in the precision grip and not the power grip. These findings have implications for individuals with a cSCI as depending on the severity of their injury to the CST they may show deficits in the performance of the precision grip but still perform actions which require a power grip.

In primates and humans there is anatomical evidence that supports the existence of corticomotoneuronal networks (CM) (Kuypers, 1981) that have been shown to control hand muscles as well as proximal muscles of the upper limb. In particular, primate models enable us to understand the direct CM system (Bennett and Lemon, 1996), which refers to the direct and monosynaptic excitatory inputs from the CST to motor neurons that elicit a muscular response (Lemon and Griffiths, 2005). Bennett and Lemon investigated the relationship between CM cell activity and target muscle activity when performing a precision grip. Two macaque monkeys were trained on a precision grip task, similar to Muir and Lemon (1983), which involved inserting the index finger and thumb into small slots that gave access to spring-loaded levers. The monkeys were then required to squeeze the two levers into a target zone and hold them there until a food reward was released. Surgical procedures involved implanting a recording chamber over the motor cortex contralateral to the trained hand and two stimulating electrodes on the CST. Intra-cortical stimulation was used to identify CM cells of the CST and monitor their activity as the precision grip was performed. EMG was also recorded from four forelimb muscles (e.g. extensor digitorum communis, flexor digitorum profundus, flexor digitorum superficialis) and four intrinsic hand muscles (e.g. first and second dorsal interossei) to correlate muscle and CM cell activity. The results showed that CM cells contributed to the complex pattern of muscle activity during the precision grip as high levels of CM cell discharge rate corresponded with high levels of muscle activity. CM cell activity was greatest during the movement phase of the task (moving the index and thumb to squeeze the levers) and not the hold phase (holding the levers in the target zone) suggesting that during dynamic movements CM cells contribute to the precise spatiotemporal muscle activity that is required to perform a precision grip.

Away from primate research the CST has also been studied in healthy humans and has been shown to have excitatory influence over different muscles at different stages of the reaching and grasping movement, i.e. the proximal muscles during the reach stage and distal muscles in the transition and grasp phase (Lemon et al., 1995). Lemon et al*.,* used kinematics, measures of grip and load force on the object surface, surface EMG and TMS during a task which required healthy human subjects to reach, grasp and lift an object using a precision grip with their right hand. Magnetic stimuli delivered by TMS to elicit excitatory drive to the CST was directed at the hand area of the contralateral motor cortex at eight different time points during the task; during the early reach, late reach, pre touch phase (as the thumb and index finger began to close around the object), touch, load (as the grip force exceeded 0.8 newtons (N)), mid load (as the grip force increased to 2.7N), between the load and movement phase (just before the object was picked up), the lift (0.2 seconds from the object being picked up) and the static phase (when the object had been held in the air for 2 seconds). The surface EMG recorded activity of the following muscles during the task, as well as the short-latency response of the muscles to TMS after each stimulation occurred; two intrinsic hand muscles (first dorsal interosseus and abductor pollicis brevis), two extrinsic hand muscles (extensor digitorum communis and flexor digitorum superficialis), brachioradialis and anterior deltoid. The results revealed that the extrinsic hand muscles, anterior deltoid and brachioradialis were subject to strong excitatory drive from the CST in response to TMS stimulation throughout the reach phase of the task, which makes sense as these muscles are responsible for the transport of the limb and formation of maximum grasp aperture. In contrast the intrinsic hand muscles showed strong excitatory drive from the CST in response to TMS later in the movement as the hand closed around the object and as the finger and thumb touched the object in order to form the precision grip. Overall this indicates that the muscles responsible for each part of the prehensile movement are subject to strong excitatory drive from the CST. Therefore this provides further support for the notion that damage to the CST following SCI may result in difficulties producing the reach and grasp phases of the movement and this will also depend on the skeletal level and severity of the SCI.

2.3 Importance of the Corticospinal tract in the control of bimanual movements

The importance of the CST in the coordination of bimanual movements comes to light in the intermanual crosstalk theory, which takes a neural perspective to describe bimanual control. It suggests that each limb has its own independent motor plan, but crosstalk of the signals controlling the two arms results in interactions between the upper limb movements. (Marteniuk and MacKenzie, 1980). As a result of this crosstalk the movement that each arm performs becomes slightly similar to the movement of the opposite arm giving rise to assimilation (evident in behavioural studies, see chapter 3), thus bimanual coordination (Mason and Bruyn, 2009). The crosstalk can occur at a low level in the spinal cord or at a high level in the cortical areas, as shown in figure 2.0. The low-level crosstalk occurs due to the contralateral and ipsilateral nature of the CST, which means that each limb receives input from each side of the brain. For example, non-differentiated commands from the right side of the brain (right motor cortex and supplementary motor area) travel down the contralateral CST to the left upper limb but also down the ipsilateral CST to the right upper limb, giving rise to interaction and coordination between the two limbs. In macaque monkeys the CST has been found to have vast bilateral projections due to its contralateral and ipsilateral nature, but also due to some CST axons crossing the midline within the spinal cord, providing anatomical support for the notion of low level crosstalk (Rosenzweig et al., 2009). Overall damage to the CST following cSCI may result in deficits in low level crosstalk and a subsequent reduction in bimanual coordination. Within the intermanual crosstalk model it is suggested that some connections are stronger than others e.g. the contralateral fibres are stronger (as 75-90% of the fibres cross the midline) than the ipsilateral fibres and the ipsilateral CST primarily innervates the proximal muscles and not the distal muscles (Brinkman and Kuypers, 1973). This is a potential mechanism giving rise to the asynchrony (temporal differences) between the limbs seen in behavioural studies (see chapter 3).

High-level crosstalk is thought to occur in cortical areas, namely the corpus callosum (nerves fibres which join the two hemispheres), as this brain structure allows for interhemispheric connections between the independent motor programs for each limb. Research in primates has provided evidence for the role of the corpus callosum in controlling bimanual movements (Cardoso de Oliveira et al., 2001). Two macaque monkeys were trained to move two separate manipulanda using a precision grip in order to move cursors on a screen into specific target zones in unimanual and bimanual conditions (symmetric, equivalent targets and asymmetric, dissimilar targets). Once the task was learnt the monkeys underwent surgical procedures to implant recording chambers above each hemisphere of the brain in order to monitor and correlate activity in each brain hemisphere during performance of the unimanual and bimanual movements. The results showed that the strongest interhemispheric correlations (via the corpus callosum) occurred in symmetrical bimanual movements, which mirrored the strongest synchrony between the limbs. In contrast, the interhemispheric correlations were weakest in asymmetrical conditions as the limbs moved asynchronously. Additionally, in unimanual movements the interhemispheric correlations were weaker than bimanual symmetrical movements. Therefore these findings suggest that interhemispheric interaction, via the corpus callosum, acts as a mechanism for crosstalk between the motor programs for the two limbs in bimanual symmetrical movements, as asynchrony between the two limbs in bimanual asymmetrical movements is associated with a reduction in the interhemispheric correlation. In addition, the interhemispheric correlations began prior to movement initiation and therefore it is feasible to assume that the corpus callosum is involved with movement planning. Although these findings provide evidence for the role of the corpus callosum it should be noted that the measurements of activity were not directly taken from the corpus callosum and inferred from correlations between the two hemispheres. As the projections from the corpus callosum are less pronounced for distal compared to proximal muscles of the upper limb (Donchin et al., 1999, Carson, 2005) this may be a potential mechanism for asynchrony between the limbs in reach to grasp movements seen in behavioural studies (see chapter 3).

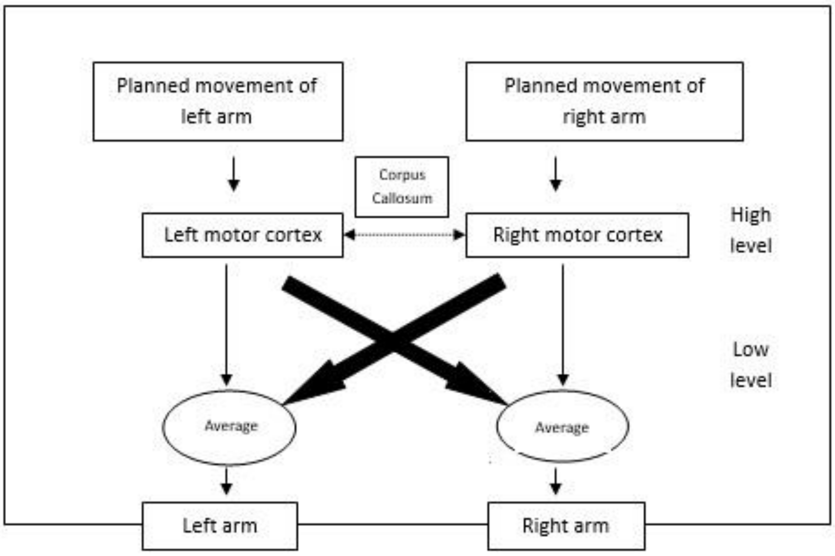

Figure 2.0: An adapted diagram of multi-level crosstalk (Cardoso de Oliveira, 2002). The movement of each upper limb is pre-planned separately but interact with each other at two levels; high level and low level. The low level crosstalk occurs through ipsilateral projections of the corticospinal tract (smaller arrows) in combination with contralateral projections (large arrows) onto a common target within the spinal cord, which cause assimilation of the two upper limb movements. The high level crosstalk occurs through the corpus callosum which allows interhemispheric connections between brain areas such as the primary motor cortex.

2.4 Importance of spinal interneurons and propriospinal neurons in the control of the precision grip

As well as the CST there are also two other indirect pathways in which descending excitation from cortical areas (e.g. Primary Motor Cortex) are transmitted to upper limb motor neurons, including spinal interneurons (within the spinal cord) and propriospinal neurons (PN) (interneurons outside of the upper limb segments of the spinal cord). These indirect pathways may act as mechanisms to regain function after injury to the CST (Lemon, 2008), especially after iSCI in which spared pathways are utilised to improve function (Marsh et al., 2011). In the cat the PNs are shown to be of great involvement in the control of forelimb reaching, however, in primates (macaque monkey) the PN involvement is less pronounced and is thought to work in parallel to CM networks in order to innervate muscles of the upper limbs (Isa et al., 2007).

Sasaki et al., investigated the effects of transecting the CST on performing a precision grip in order to gain insight into the contribution of PNs in primates (Sasaki et al., 2004). Three macaque monkeys were trained to perform a precision grip task (retrieving food from a horizontal tube), which was then followed by a complete unilateral transection of the CST (at C4/C5). Following the transections precision grip performance for each monkey deteriorated, namely in the form of deficits in preshaping the hand and force production, thus supporting the importance of the CST. However, the continued ability to perform a precision grip, despite deterioration, and the improvement in precision grip performance over subsequent days/weeks suggests that other pathways may be involved in the control of the precision grip, such as the PN networks. This suggestion was supported by electrophysiological recordings of motor neurons of both (intact and lesioned) sides of the spinal cord as the lesioned side showed disynaptic (identified due to latency 1.0-1.8ms as opposed to monosynaptic latency of 0.4-1.0ms) CM excitation remained after the CST transection, which was mediated via C3-C4 PNs. Along with these findings by Sasaki et al., the fact that direct CM connections are excitatory suggests that inhibitory control must come from indirect pathways such as the PNs (Lemon and Griffiths, 2005) and therefore the direct CM connections are likely to work in parallel with indirect connection such as the PNs in order to control the precision grip (Lemon, 2008). Recent work has also shown that PNs may also be an important substrate for recovery after SCI as their intersegmental projection pattern and large population suggests that they are capable of ‘bridging’ an iSCI (Flynn et al., 2011).

In addition to PNs pre-motor spinal interneurons (C5-T1) have also been shown to activate multiple finger muscles when performing grasping movements and therefore function to co-activate muscles of the hand during performance of the precision grip (Takei and Seki, 2010). Three macaque monkeys were trained on a precision grip task, which involved reaching and grasping for two manipulanda that comprised of two spring loaded levers (bimanual task). The monkeys were trained to apply force to the levers until they were positioned into a target location, hold the position (1-2 seconds) and then release the levers. Following training the monkeys underwent a surgical procedure in order to implant recording/stimulating electrodes over the cervical spinal cord, in order to identify premotor spinal interneurons, and muscles of the arm and hand e.g. biceps brachii, triceps brachii, dorsal interossei and finger flexors and extensors. The results showed that spinal interneurons activated multiple finger muscles (co-activation) in both limbs and therefore play an important role in bimanual coordination during grasping.

In a subsequent study spinal interneurons have been shown to be involved with both the dynamic (changes in grip force) and static (hold phase) phases of the precision grip (Takei and Seki, 2013). Similar to the previous study three monkeys performed the bimanual precision grip task whilst recordings from the cervical spinal cord and arm and hand muscles were obtained. In this study spinal interneuron activity was correlated with changes in grip force (measured by the potentiometer and strain gauge in the levers of the manipulanda). The results showed that grip force was correlated with phasic (fast) and tonic (slow) activity of spinal interneurons during the dynamic and static phases of the precision grip task. Some spinal interneurons showed early onset and pure phasic facilitation during the dynamic section of the task (grasping the levers) and some showed late onset and pure tonic facilitation during the static section of the task (holding the levers in position). Therefore pre-motor spinal interneurons show an indirect contribution of the CM network to both force production and force maintenance.

2.5 Importance of the Reticulospinal tract in the control of the precision grip

Riddle et al., (2009) implanted a stimulating electrode into the right upper medulla of anaesthetised monkeys in order to stimulate the RST whilst recording activity of the nerves, which innervated muscles of the proximal (e.g. radial nerve which innervates muscles of the shoulder) and distal upper limb (e.g. median and ulnar nerve which innervate finger flexors and intrinsic hand muscles). The results revealed that direct RST excitatory connections innervate both the proximal and distal muscles of the upper limb similarly suggesting that the RST is not solely responsible for the control of more proximal upper limb muscles. It also suggests that neurons of the RST are in a position to act as a substrate for recovery after damage to the CST following SCI.

Further to this, research has suggested that the RST converges with the CST in order to control the upper limbs (Riddle and Baker, 2010). Two adult monkeys were trained on a food retrieval task whilst EMG activity was collected from muscles of the right hand (abductor pollicis brevis, flexor digitorum superficialis and flexor digitorum profundus). Stimulating electrodes were surgically placed on the left CST (contralateral to the hand performing the task) and right RST, and recording electrodes were also implanted to monitor activity of the spinal interneurons (C6-

C8). The results revealed that when completing the food retrieval task, along with stimulation of the CST and RST, the spinal interneurons received excitatory input from both the CST and RST. This convergence was also shown in the grasp phase of the task and when the monkey was required to make distal wrist and finger movements in order to complete the food retrieval. Overall the study revealed the overlapping effects of the CST and RST on spinal interneurons and therefore suggests that both of these descending pathways may be important substrate for recovery.

2.6 Conclusion

This chapter addresses the various spinal structures that have been shown to control the precision grip, which is the focus of the studies within this thesis. Firstly, the evidence in primates suggests that the CST and the direct, monosynaptic, excitatory inputs from the CST to motor neurons, known as the corticomotoneuronal network, contribute to the control of the precision grip, specifically the production of grip force between the index finger and thumb. The role of the CST has also been supported in humans as proximal and distal muscles were subject to strong excitatory drive throughout the reach and grasp movement. The CST is also thought to gives rise to low-level crosstalk between the upper limbs due to its contralateral and ipsilateral nature giving rise to bimanual coordination between the upper limbs, as described by the Intermanual crosstalk theory. Therefore the summation of all evidence discussed suggests that injury to the spinal cord, and specifically the CST, will result in deficits in the control of the precision grip both unimanually and bimanually, but also be a mechanism for recovery as neuroplasticity in the CST has previously been shown to induce improvements in function (see chapter 1, section 1.4.2). Indirect pathways such as propriospinal neurons and spinal interneurons have also shown activation in the control the precision grip. Propriospinal neurons are thought to work in parallel to the CST and form a potential substrate for recovery, especially following icSCI. Pre-motor spinal interneurons in the cervical spinal cord have been shown to co-activate multiple finger muscles bimanually in both the dynamic and static phases of the precision grip. Finally, the RST, an ipsilateral descending pathway, has been shown to innervate muscles of the proximal and distal upper limb and is suggested to converge with the CST in order to control the precision grip. If damage to the CST occurs during in SCI then the RST could act as a potential substrate for recovery. The following chapter will report findings from behavioural studies addressing the control of the precision grip during prehension (reaching and grasping) in non-injured individuals.

Chapter 3 Typical Prehension

3.1 Introduction

Prehension, most simply described as reaching and grasping, is a coordinated movement which involves directing the arm to the spatial location of the target (transport phase) and grasping a three dimensional object (grasping phase). Both involve a large number of muscle and joints, thus, degrees of freedom (Jeannerod, 1984, Bernstein, 1967). Reaching and grasping is a frequently performed task in daily life and has been widely researched due to its' ability to help us obtain a greater understanding about how the nervous system coordinates multi-joint actions (Wang and Stelmach, 2001). In relation to this thesis, the understanding of how the nervous system coordinates unimanual and bimanual prehension in non-injured participants helps us to determine how this control changes after cSCI.

Firstly, this chapter reviews the current literature regarding typical unimanual (one handed) prehension and, in particular, the effects of object distance (extrinsic properties) and object size (intrinsic properties) on the transport and grasp phases of prehension, as well as the effects of aging on prehension. The latter is important due to the aging population of those sustaining a SCI (Thompson et al., 2014). Secondly, as most activities of daily living (feeding, dressing) require the use of both limbs simultaneously, i.e. bimanual coordination, this chapter reviews the current literature comparing unimanual and bimanual prehension in non-injured participants, as well as the effects of aging on bimanual coordination. It is important to note that the research reviewed in this chapter varies in methodology, particularly in task (reaching only and reaching and grasping), but the general findings help us to understand how prehension is controlled.

3.2 Unimanual prehension

3.2.1 The transport phase

The transport phase is concerned with directing the arm to the spatial location of the target and requires the control of proximal muscles (e.g. anterior deltoid, pectoralis major, triceps brachii, biceps brachii) and joints (shoulder and elbow) as the arm travels towards the target. The kinematic velocity profile of the transport phase is typically a 'symmetrical bell shaped' curve as the upper limb accelerates towards to the object and then decelerates to ensure that the object is picked up accurately (Jeannerod, 1984). Early research suggested that object size did not influence the transport component (Jeannerod, 1981). However, later research indicated that the smaller the object, the greater the movement time (time between movement onset and end of movement) due to a prolonged deceleration time (time between peak velocity and end of movement) (MacKenzie et al., 1987, Marteniuk et al., 1990, Jakobson and Goodale, 1991, Wang and Stelmach, 2001). Object distance/amplitude has also been shown to influence the transport component as the greater the object distance, the greater the peak velocity (maximal velocity during the movement) and longer the movement time (Jakobson and Goodale, 1991). The effects of object size (3,5,7 and 9cm) and object distance (20 and 30cm) on the transport phase of prehension have been related to Fitts' law (Bootsma et al., 1994), which demonstrates a lawful relationship between the speed and accuracy of movement, i.e. the faster the movement, the more the accuracy is compromised (Fitts, 1954). Bootsma et al., (1994) found that the smaller the object size (width) and larger the object distance, the longer the movement time due to a prolonged deceleration phase. Therefore, in line with Fitts law, the time taken to pick up the object increased in a linear fashion with task difficulty (larger object distance, smaller object size) so not to compromise accuracy.

In general, the majority of the distance to the target is covered by a primary ballistic submovement. However, if there are any errors in this primary submovement (as a result of poor planning or execution) then subsequent submovements (usually measured via zero crossings in the acceleration profile (Steenbergen and Van Der Kamp, 2004) are introduced in order to improve accuracy of the transport of the limb to the target (Fradet et al., 2008). Research by Fradet et al., (2008) has shown that the faster the primary submovement, i.e. the higher the peak velocity, the greater the number of subsequent submovements needed. However, the accuracy requirements of the task also influences the number of submovements as the greater the accuracy demands of movement termination, the more submovements are performed.

As the transport component requires the coordination of forces produced by proximal muscles (Zatsiorsky et al., 2003) EMG and kinematic measures have been combined to investigate the effects of manipulating object distance on muscle activation of the shoulder and elbow in non-injured adults (Bonnefoy et al., 2009). Ten volunteers performed palmer reach to grasp movements at 20, 30 and 40cm for a cylindrical object with their right hand. EMG signals recorded the activation of the anterior deltoid, posterior deltoid, triceps brachii, biceps brachii and brachioradialis. The results indicated that reaching to farther object distances led to increased muscle amplitude and, therefore, greater muscle activation in the muscles tested. This is because reaching farther requires more arm extension and, therefore, activation of each muscle to generate enough force to move the shoulder and elbow joints. Also, the agonist-antagonist muscle co-activation between the triceps brachii (agonist) and biceps brachii (antagonist) was reduced for nearer distances in comparison to farther distances. This could be related to the amount of force needed to apply a braking force to the upper limb, which is usually carried out by the biceps brachii (Hughes et al., 2009) as reaching to farther objects results in a greater peak velocity and therefore requires more muscle activation of the biceps brachii in order to slow the limb down. In this study, the timing of the muscle activity was not measured so we cannot identify a pattern of muscle activity for each stage of the prehensile movement e.g. start, acceleration to peak velocity, deceleration and object pick up. This would allow us to relate the EMG analysis to kinematic events and provide an understanding of which muscle contributes to each stage of the reach to grasp movement. In relation to individuals with a cSCI, it will allow us identify how muscle activity patterns differ to non-injured controls as the muscles contributing to reaching have already been shown to differ due to paralysis of shoulder and elbow muscles (Koshland et al., 2005) (see chapter 4, section 4.2).

3.2.2 The grasp phase

The grasp phase is concerned with grasping the three dimensional object and involves more distal muscles (e.g. flexors and extensors of the wrist and fingers) as the digits come into contact with the target or object (Jeannerod, 1984). Research has suggested that the grasp phase is influenced by object size (Bootsma et al., 1994) as the greater the object size (width), the larger the maximum grasp aperture (MGA, distance between the index finger and thumb). Thus, MGA is scaled to object size. Manipulating object size has also been shown to influence the timing of MGA as the smaller the object the earlier in the movement MGA occurred (Marteniuk et al., 1990). In addition, Marteniuk et al., (1990) found that the size of the object to be grasped was consistently overestimated and both of these findings were thought to be an error compensating mechanism as overestimation and earlier hand opening allows for corrections of hand placement around the object. Overestimation of object size has also been suggested to allow for faster movements to be produced as increasing movement speed towards an object results in a larger MGA formation (Wing et al., 1986).

There has been some debate regarding the relationship between the transport and grasp phases as early research suggested that changes in the size of the object did not affect the transport component whilst changes to object distance affected the transport phase and not the grasp phase, suggesting that the two components are not coupled (Jeannerod, 1981). However, further research has suggested that timing of peak deceleration of the transport phase coincides with the timing of formation of MGA in the grasp phase, thus, suggesting the two phases are coupled (Jeannerod, 1984). Both object size and object distance have also been shown to influence the transport phase in terms of movement time, providing further support for the coupling of the two phases (MacKenzie et al., 1987, Marteniuk et al., 1990, Bootsma et al., 1994). Finally, on a muscular basis prehension involves considerable overlap between the transport and grasp phases suggesting that the two phases are coupled. This is because the shoulder (abduction/adduction, flexion/extension), forearm (supination/pronation) and wrist (flexion/extension) positioning during the transport phase prepare the hand for grasping the object (Marteniuk et al., 1990).

3.2.3 The importance of vision in unimanual prehension

In order to successfully reach and grasp an object, it is important to know the location of the object (extrinsic properties) in space and the characteristics of the object (intrinsic properties), highlighting the importance of vision. Marteniuk et al., (1990), suggested that overestimation of object size to allow for error correction and hand placement around the object shows a clear visuomotor link between the physical attributes of the object and the control of the hand. Jakobson and Goodale (1991) conducted a study using fifteen participants whereby visual feedback was manipulated when reaching and grasping using a precision grip. The results showed that of the removal of vision of the arm and object shortly after movement onset caused MGA to be exaggerated and occur earlier in the movement, suggesting that removal of visual feedback influences the movement pattern.

3.2.4 The importance of proprioception in unimanual prehension

The ability to process sensory information from muscle and joints (proprioception) in order to establish limb position also plays an important role in reaching (Ghez et al., 1990). Gordon et al., (1995) compared neurologically intact participants and participants with a loss of proprioception (deafferented patients) whilst performing a reaching task. The task required participants to move a cursor on a screen from a start position to a visual target using their dominant hand. Visual feedback was also manipulated as vision of the cursor on the screen was removed so that visual feedback of limb trajectory and accuracy was removed. The results showed that the participants with a loss of proprioception displayed less accurate movements with more end-point errors compared to intact participants and lack of vision accentuated the differences. Thus, not only does visual feedback contribute to successful reaching but so does proprioception (Gordon et al., 1995). This study implies that following cSCI, there may be an increased reliance on visual feedback in order to successfully complete a reach-to-grasp movement due to deficits in sensory, including proprioceptive, function.

3.2.5 Unimanual prehension in older adults

The above studies have focused on unimanual prehension in non-injured, young adults (Jeannerod, 1984, Jakobson and Goodale, 1991, Bootsma et al., 1994, Bonnefoy et al., 2009) but, as the age of those sustaining a SCI is increasing, it is important to consider the effects of aging on prehension (Thompson et al., 2014). With aging, there are natural declines in the ability to process sensory (e.g. visual) information (Sosnoff and Newell, 2006), and in the ability to manipulate objects (manual dexterity), both of which may impact prehensile behaviour (Williams et al., 1982, Hackel et al., 1992). In an aiming task, older adults have been shown to produce movements that are slower and longer than younger adults due to a prolonged deceleration phase (Goggin and Stelmach, 1990). Older adults have also been shown to rely more heavily on visual feedback than younger adults, especially towards the end of the movement (evidenced by an increased time spent decelerating when vision of the arm was removed) in order to correct any errors in the transport of the limb to the target (Seidler-Dobrin and Stelmach, 1998). Although these two studies looked at aiming (reaching) movements and not prehension, they can be used to support the theory that differences exist between younger and older adults in terms of an increased importance of the deceleration phase.

Following this pattern of research findings in aiming movements, Coats and Wann (2011) conducted two studies. The first investigated the dependence of younger and older adults on vision of the hand when placing a small peg into one of three cued targets (Coats and Wann, 2011). The results indicated that differences in performance between younger and older adults emerged only when vision of the hand was removed. This took the form of undershooting the target hole initially, and so producing a secondary submovement in order to successfully place the peg into the target. In a second experiment, the same participants' vision was manipulated when reaching and grasping objects of different sizes at different distances to determine whether precision requirements of the task elicited greater differences between younger and older adults. The results again indicated that the groups' differed only when vision of the hand was removed. However, the differences emerged in the final approach to the object, which the authors identified as the final adjustment phase. This may be due to the older adults needing to make more adjustments in order to accurately pick up the object. The results from both experiments suggest that older adults rely more heavily on visual feedback for correction of errors than their younger counterparts and as the reaching and grasping movement progresses.

However, vision may not be the only factor contributing to performance differences between younger and older adults in completing different activities such as fastening buttons, opening jars and picking up objects when precise control of force is required (Voelcker-Rehage and Alberts, 2005). It is established in the literature that, with age, there are declines in force modulation as older adults produce excessive force when lifting and holding objects which may be due to loss of tactile sensation (Cole, 1991). It could also be due to changes in the motor system, such as reduction of tactile sensation and strength, resulting in degeneration of upper limb function (Cole et al., 1998). Voelcker-Rehage and Alberts (2005) used a precision grip task to investigate force modulation in young and older adults in a tracking task. The results indicated that older adults were significantly poorer at modulating force than younger adults and, therefore, displayed reduced ability in the tracking task. Although this task was not explicitly related to performing reach to grasp movements using the precision grip, it highlights that force modulation during the precision grip may be another reason for age-related differences in prehensile movements as they require more time to produce enough force to pick up the object.

3.3 Bimanual prehension

Many activities of daily living such as feeding, dressing and washing require the use of both upper limbs and are referred to as bimanual movements. A vast amount of literature has focused on how the upper limbs are coordinated both spatially (e.g. maximum grasp aperture, number of adjustments) and temporally (e.g. movement time, peak velocity and time difference between the limbs reaching kinematic events) during bimanual prehension movements in non-injured adults. In addition, some bimanual tasks require similar movements from the two hands (symmetrical), e.g. when using both upper limbs to reach and grasp a large object, whilst some require different movements from each upper limb (asymmetrical), e.g. when one hand opens a cupboard door whilst the other reaches to grasp an object such as a jar or glass. With this in mind, how task symmetry affects prehensile movements has also been investigated. This research gives us an idea of the underlying control mechanisms in bimanual tasks and the level of synchrony between the limbs, i.e. whether the limbs mirror each other or show differing movement patterns. The following section discusses the research based on coordination of the upper limbs in bimanual tasks, how bimanual movements differ to unimanual movements, and the effects of aging on bimanual coordination.

3.3.1 Bimanual coordination

Early research suggested that during bimanual tasks, the upper limbs move synchronously, acting as a functional, synergistic unit, despite differing activities of the arms (Kelso et al., 1979), i.e. different distance and speed of the two limbs. This was supported by further research that manipulated distance and size of the objects to be reached and grasped (precision grip) in both unimanual and bimanual conditions (symmetric e.g. both hands reaching to objects 20cm away and asymmetric e.g. one hand reaching for an object 20cm away and the other hand reaching for an object 30cm away) (Jackson et al., 1999). For the distance and size study, the results revealed that bimanual reaches were significantly longer in duration and slower (lower peak velocity) than unimanual reaches of equivalent distance and size. Additionally, in bimanual conditions, the hands reached a greater MGA and reached MGA earlier than in unimanual conditions. This may be a strategy for error correction and hand placement around the objects as errors are more likely due to increased task difficulty. Overall, these differences between unimanual and bimanual movements are collectively known as bimanual cost which is suggested to emerge in order to maintain synchrony between the limbs during bimanual movements (Jackson et al., 1999). Jackson et al., (1999) found that bimanual cost arose regardless of whether the bimanual movements were symmetrical or asymmetrical in nature. In terms of synchrony, the results revealed no significant time difference between the limbs starting the movement, reaching peak velocity or at object contact for the symmetrical and asymmetrical conditions as the upper limbs remained synchronised. This meant that despite each limb moving different distances or to objects of difference sizes in the asymmetrical condition, the limbs remained temporally coordinated throughout the bimanual movement.

Taken as a whole, the research by Kelso et al., (1979) and Jackson et al., (1999) postulates that, during bimanual movements, the nervous system prefers to place temporal constraints on the muscles of both upper limbs, spanning multiple joints, so that they are constrained to act as a single, functional unit or coordinative structure (Turvey, 1977), thereby reducing the degrees of freedom to be controlled (Bernstein, 1967). However, this suggestion does not take into account the role of feedback, e.g. visual feedback, when controlling bimanual movements. The next sections of this chapter will address the role of visual feedback and proprioceptive feedback in bimanual coordination and how it induces asynchrony between the limbs.

3.3.2 The role of vision in bimanual coordination

Despite this early evidence of synchrony between the limbs during bimanual prehension, recent research has found asynchronous timing, and postulates that perceptual constraints, i.e. visual feedback, are the reason for asynchrony between the limbs. The theories of coordinative structures and intermanual crosstalk (see chapter 2, section 2.3) do not explain how the visual system is able to provide online control of bimanual movements (Miller and Smyth, 2012). In an aiming study comprising of six adults, target size and distance were manipulated whilst participants moved a stylus in each hand from the start position to the prompted (audio and visual) targets in bimanual symmetric and asymmetric conditions (Riek et al., 2003). The results showed that, during all bimanual movements, the limbs were coordinated to start and end the movement of the two limbs as synchronously as possible, but during the movement e.g. at peak velocity, asynchrony between the limbs emerged. In order to fix this asynchrony before the end of the movement, participants often used a ‘hover phase’, which allowed the participants to rapidly transport one hand to a target and then wait for the other hand to be spatially positioned before completing the movement. This ‘hover phase’ was postulated as an opportunity for visual feedback to be used in order to correct any errors, e.g. spatial errors of the hands, before both hands reached the end-point of the movement (Riek et al., 2003). The results also showed that the ‘hover phase’ was greater in conditions where the distances of the targets were asymmetrical, i.e. one hand was reaching further than the other. Therefore, the ‘hover phase’ was greater in tasks where vision becomes a constraint as both targets cannot be visually fixated at the same time, a limitation to the human visual system.

This importance of vision in bimanual tasks was also supported in a prehension task (precision grip), whereby younger adults reached and grasped objects varying in size and distance in both symmetric and asymmetric conditions (Mason and Bruyn, 2009). The first experiment revealed that movement time was similar regardless of object size, but deceleration time was significantly longer when reaching for the two smaller objects than larger objects as precision requirements increased. In relation to the grasp phase, MGA was smaller and reached significantly earlier when reaching to the small object compared to large object, resulting in significant differences between the limbs in asymmetrical conditions. In symmetrical conditions, there was synchrony between the limbs at the start of the movement and peak velocity, but temporal asynchronies began to emerge after this point as the authors postulated that vision became a constraint and shifts in gaze between the objects became necessary to successfully grasp the objects. In the asymmetrical conditions, the asynchronies started to occur earlier than peak velocity.

In the second experiment, the results revealed that in the symmetrical conditions, movement time, deceleration time and peak velocity, were similar for both limbs in near and far distance conditions. However, in asymmetrical conditions, higher peak velocity and longer movement time were evident for the limb moving to the far object than the limb moving to the near object. The results also indicated the movement of the upper limb to the far object influenced the movement of the limb to the near object and vice versa. This resulted in the movement time for the limb moving to the near object increasing when compared to the symmetrical conditions but the movement time to the far object decreasing. This provides support for neural crosstalk (Marteniuk and MacKenzie, 1980) between the limbs as the movement of one limb influenced movement of the other limb and, thus, movement assimilation. With regards to the grasp phase, there was no significant main effect of condition on MGA size but, in asymmetrical conditions, MGA was reached earlier in the movement for the limb moving to the near object compared to far object. The synchrony results were similar to experiment one in that asynchrony was greater in asymmetrical conditions. However, the authors suggested that the results of experiment two support the notion of the 'hover phase' (Riek et al., 2003) as the hand reaching to the near object hovered above the object (increasing movement time compared to symmetrical conditions) whilst the hand moving to the far object was still in the transport phase and required visual feedback for guidance of the arm/hand towards the object. Overall, the need for visual fixation shifts became more important as the limbs were transported further away from the body, which resulted in progressive asynchrony.

3.3.3 The role of proprioceptive feedback in bimanual coordination

Despite vision playing an important role in synchronisation between the limbs during bimanual movements as discussed above, research has suggested that other factors such as proprioception may have an important role in bimanual coordination (Bruyn and Mason, 2009). Bruyn and Mason recorded kinematics and eye movements of eleven participants when reaching and grasping to symmetrical and asymmetrical objects using a precision grip when distance of the targets was manipulated. The experiment manipulated vision under four conditions: natural vision, fixate-left (fixate on left object), fixate-right (fixate on right object) and fixate-centre (between the two targets). The results revealed that asynchrony in asymmetrical conditions was evident regardless of visual condition suggesting that vision may not be the sole cause of asynchrony. Bruyn and Mason (2009) postulated that proprioception in combination with vision may play an important role in bimanual coordination as in the fixate-left and fixate-right conditions proprioceptive feedback was received but vision was constrained. Overall, these findings may have implications for individuals with a cSCI as a reduction in sensory and proprioceptive feedback following cSCI could reduce the ability to coordinate the limbs and could cause an increased reliance on visual feedback as a compensatory strategy.

3.3.4 Bimanual coordination in older adults

As suggested in the previous section, vision and proprioception are an important aspect of bimanual coordination and as it is well known that with aging there are natural declines in the ability to process sensory information (Sosnoff and Newell, 2006). Early work by Stelmach et al., indicated that older adults displayed longer movement times in unimanual and bimanual (symmetric and asymmetric) aiming conditions when compared to young adults (Stelmach et al., 1988). In the bimanual movements, the older adults also showed greater asynchrony at the start of the movement which was not corrected for and resulted in greater asynchrony at the end of the movement. Hence, this suggests that aging results in a decrement to bimanual coordination.

More recently, symmetrical and asymmetrical bimanual prehension has been compared in younger and older adults (Coats and Wann, 2012). The task involved moving from a start position, picking up two objects and placing them in one specified end location in synchrony (one of three trays). The authors introduced final adjustment time into their analysis of bimanual movements, which quantified the time between the velocity of the object dropping to 3% of peak velocity and the object being placed into the tray. This differs to hover time, which was first introduced by Riek et al., (2003), as this is the time between velocity dropping to 10% of peak velocity and the object being placed. The results showed that in terms of overall movement time, there was no significant difference between groups. However, the older adults spent a longer amount of time in the final adjustment phase and made more adjustments during this phase (identified by zero crossings in acceleration) compared to younger adults. Overall, the results suggest that the older adults moved more quickly towards to the tray, which is supported by a higher peak velocity, but with little accuracy. Then the older adults relied on the final adjustment phase to correct any errors/make adjustments before object placement in the specified location. This supports the notion that older adults find online control of movements problematic and correct errors when both objects can be visually fixated, i.e. at the end of the movement before object placement. In terms of synchrony, there were no significant differences at the start of movement or at peak velocity between young and older adults, but the older adults were more synchronous at the end of the movement demonstrating the importance of the final adjustment phase.

3.4 Conclusion

This chapter addresses the control of typical unimanual and bimanual prehension, which is important when trying to understand how control of this multi-joint movement changes after cSCI. In sum, the unimanual prehension literature in younger adults has indicated that object distance and object size influence the transport phase e.g. increasing object distance and decreasing object size results in longer movement time. Object distance has also been shown to influence muscle activity as farther reaches require greater muscle activation in order to extend the shoulder and elbow towards the object. The grasp phase of prehension has been shown to change with object size as smaller objects result in smaller MGA formation that occurs earlier in the movement.

With regards to bimanual prehension, the difference to unimanual prehension and synchrony between the limbs was discussed. Overall, it is suggested that visual constraints induce asynchrony between the limbs in younger adults as it is not possible to fixate both limbs at once and this is accentuated in asymmetrical conditions. The importance of the role of vision and proprioception in the control of unimanual and bimanual prehension discussed in this chapter can be related to individuals with a cSCI due to their declines in sensory function. The effects of aging on prehension were also addressed as the population of those sustaining a cSCI is increasing in age and, therefore, will differ to younger adults as aging is associated with longer (duration), slower movements with an increased reliance on visual feedback. Now that typical prehension has been addressed, the next chapter will focus on the existing literature based on upper limb kinematics and EMG after cSCI.

Chapter 4 Prehension after Cervical Spinal Cord Injury

4.1 Introduction

A cervical Spinal Cord Injury (cSCI) leads to deficits in arm and hand function and regaining this is a high priority during rehabilitation (Anderson, 2004, Snoek et al., 2004). With regards to prehension a cSCI at the skeletal level C5 to C6 impairs the ability to actively extend the elbow against gravity, i.e. the transport phase of prehension, and at C5 to C7 impairs grasping ability (Mateo et al., 2015). Due to this impairment individuals with a cSCI develop new neuro-motor strategies in order to control upper limb movement (Koshland et al., 2005). Therefore, before designing successful rehabilitation strategies it is important to understand how the upper limbs are controlled following cSCI and how this differs to non-injured participants. In Spinal Injury Centres clinical (ASIA) and functional assessments (e.g. Spinal Cord Independence Measure-III) are generally used to quantify arm and hand function, however, literature suggests that kinematic and EMG measures provide more detail and allow stronger characterisation (e.g. movement time, peak velocity, muscle activation patterns) of upper limb function following cSCI (de los Reyes-Guzman et al., 2010, Jacquier-Bret et al., 2008, Jacquier-Bret et al., 2009). This chapter addresses the literature describing kinematic and EMG analysis of unimanual reaching and grasping after cSCI as to date there is no published literature that investigates control of bimanual reaching and grasping following cSCI.

4.2 The transport phase

There is a general agreement within the literature that following cSCI at C5-7 there is some preservation of kinematic features in the transport phase that resemble those of non-injured control participants (Laffont et al., 2000, Laffont et al., 2007, Koshland et al., 2005, Mateo et al., 2013, Hoffmann et al., 2006, Jacquier-Bret et al., 2009). These features include a ‘smooth bell-shaped’ velocity profile and straight finger paths. However, the temporal differences that emerge include a lower peak velocity and longer movement time than non-injured participants, which results from a prolonged deceleration phase of the limb reaching the target location (Mateo et al., 2013, Hoffmann et al., 2006, Laffont et al., 2007, de los Reyes-Guzmán et al., 2010, Laffont et al., 2000). These findings have been supported in different task contexts; reaching to a target (aiming) (Mateo et al., 2013, Hoffmann et al., 2006, Laffont et al., 2000) and in reach-to grasp tasks (Mateo et al., 2013, Laffont et al., 2007, de los Reyes-Guzmán et al., 2010, Laffont et al., 2000). This movement slowing has been suggested to be a strategy to preserve accuracy of the movement as per the speed accuracy trade off (Mateo et al., 2015, Fitts, 1954). Alternatively the motor slowing (longer movement duration, lower peak velocity and lower acceleration peaks) seen in participants with cSCI could be a strategy to deal with the loss in ability to slow their arm down due to reduced triceps brachii and biceps brachii strength (Gronley et al., 2000, Wierzbicka and Wiegner, 1992) and subsequent lack of agonist-antagonist co-contraction (Koshland et al., 2005). This is because the agonist-antagonist co-contraction between the triceps brachii and biceps brachii generally serves to stop movement in non-injured participants (Koshland et al., 2005), allowing them to produce a higher peak velocity and acceleration peak. Research has also shown that individuals with a cSCI (C5-C6) reach lower acceleration and deceleration peaks, which are multiple in number, when transporting the limb to a target than non-injured participants (Koshland et al., 2005). Therefore the reaching movement is less smooth than non-injured control participants and requires more adjustments to be made in order to successfully reach the target.

In terms of differences in spatial measures between participants with a cSCI and non-injured participants, studies have shown an increased reliance on the shoulder complex in order to achieve elbow extension by showing increased displacement of the shoulder (acromion marker) and rotation of the scapula (Hoffmann et al., 2006, Laffont et al., 2000, Popović and Popović, 1994). This is also supported by EMG studies (Koshland et al., 2005, Janssen-Potten et al., 2008, Jacquier-Bret et al., 2009) as muscle activity of the shoulder complex (e.g. anterior deltoid, posterior deltoid and pectoralis major) is utilised to produce passive elbow extension due to the lack of triceps brachii activation following cSCI. Koshland et al., (2005) described this as evidence of motor redundancy following cSCI as the reach to grasp movement was completed using novel muscle activity. The notion of motor redundancy postulates that there are multiple muscle solutions in order to produce the same kinematic movement. The new muscle activity pattern also suggests that reorganisation of spared pathways (see chapter 1, e.g. axonal sprouting of spared fibres of the corticospinal tract) following SCI has occurred giving rise to new muscle activity patterns to preserve function.

Only one study has quantified how manipulating object distance influences prehension after cSCI. Laffont et al., (2000) documented reaching and grasping (using a precision grip) in four individuals with a C6 complete cSCI, and five non-injured participants. The object was placed at a short (object at the level of the wrist) or long distance (object at the level of the metacarpo-phalangeal joint; knuckle) as a function of each individuals arm length. The results showed that for both non-injured participants and participants with a cSCI movement time was longer (duration) for the far distance condition, but peak velocity was higher as reported in previous research (see chapter 3, section 3.2.1; (Jakobson and Goodale, 1991, Bootsma et al., 1994).

4.3 The grasp phase

Research relating to the grasp phase of prehension has mainly been focused on the compensatory strategy adopted by individuals with a C6 cSCI. This is termed the tenodesis grasp and it emerges due to paralysis of the finger and thumb extensors and flexors (Mateo et al., 2015). The tenodesis grasp involves extension of the wrist (extensor carpi radialis) in order to produce passive finger flexion to grasp an object. Kinematic evidence suggests that individuals with a C6 cSCI display wrist flexion in the transport phase and wrist extension (to allow passive finger flexion) in the grasp phase (Mateo et al., 2013, de los Reyes-Guzman et al., 2010). These differences in wrist orientation between the transport and grasp phases suggest that individuals with a C6 cSCI complete prehension via two successive stages (Mateo et al., 2013). This notion is also supported by Hoffman et al., who reported temporal dissociation between the transport and grasp phases in individuals with a C6/C7 cSCI and therefore implies sequential planning of the two stages of prehension following cSCI (Hoffman et al., 2002). However, the kinematic evidence of the tenodesis grasp is not supported by differences in muscle activity as Jacquier Bret et al., 2009 concluded that EMG measures revealed no significant difference in extensor carpi radialis activity between non-injured participants and participants with a cSCI.

Laffont et al., (2007) identified how individuals with a C6-C7 cSCI grasped balls of different sizes and weights when compared to non-injured participants with no specification of the type of grip that should be used. The results highlighted that despite cSCI hand configuration was similar to non-injured participants and the precision grip was the most popular grip chosen to execute the task. Therefore changes in finger muscle strength and a reduction in the degrees of freedom in the hand following cSCI have little influence over hand configuration and grip choice.

Recently, research has quantified the ability to modulate hand aperture (MGA) in relation to object size following chronic (3-16 years) C5-C7 cSCI (Stahl et al., 2014). The task involved participants using their dominant hand, to firstly perform their maximum hand opening (taken as the maximum distance between the index finger and thumb). Following this participants were instructed to reach and grasp balls of differing sizes using a precision grip. The results showed that maximum hand opening was reduced in participants with cSCI (10-11cm) compared to non-injured participants (14cm). However, participants with cSCI were still able to modulate their MGA in relation to ball size, i.e. MGA increased with ball size. Stahl et al., (2014) also used EMG measures to quantify differences in distal muscle activity between participants with a C5-C7 cSCI and non-injured participants. The results of this analysis showed that with increasing ball size the participants with a cSCI showed greater activation of the wrist flexor (flexor carpi ulnaris) than the wrist extensor (extensor carpi ulnaris) in order to maximise maximum grasp aperture. This differs to non-injured control participants who showed a similar amount of activation in the wrist flexor and extensor. Overall this extends the evidence for novel neuro-motor control strategies following cSCI denoting reorganisation in the nervous system and motor redundancy agreeing with Koshland et al., (2005).

4.4 Conclusion

In a variety of unimanual reaching and reach-to-grasp tasks studies have shown that despite injury to the cervical spinal cord individuals with chronic cSCI are still able to produce similar kinematic features (smooth bell-shaped velocity profile, straight finger paths, ability to modulate grasp aperture to object size) to non-injured individuals. However, the movements are at a slower pace (longer movement time due to a prolonged deceleration phase) and with increased reliance on the shoulder complex to produce extension of the elbow (increased displacement of the shoulder and greater activation of shoulder musculature). Individuals with a cSCI have also been shown to use the precision grip in order to grasp objects, and scale their hand aperture to object size despite their reduction in maximal hand opening and deficits in finger muscle strength.

To date there has been no one study that has quantified how the upper limbs reach and grasp objects bimanually and if coordination between the limbs is maintained following cSCI. This is important when considering the development of bimanual training paradigms as kinematic and EMG analysis allows for detailed description of how control changes following a cSCI compared to non-injured participants.

Chapter 5 General Methods

5.1 Introduction

Many of the methods and procedures are common to the three studies within this thesis. To avoid repetition of these general methods and procedures they are presented in this chapter. Any methodological differences between each study will be presented in the relevant chapter.

5.2 Overview of participant selection

Participants for all studies within this thesis had either an incomplete cervical Spinal Cord Injury (icSCI) or were non-injured control participants.

5.2.1 Initial selection

Eighteen participants with an acute icSCI (Mean age=61.61±15.24 years) who were inpatients at the Yorkshire Regional Spinal Injuries Centre and North West Regional Spinal Injuries Centre volunteered for participation (see table 5.0 for participants with icSCI characteristics). The inclusion criteria were as follows; >18 years of age, capable of giving written consent for themselves, an icSCI at the skeletal level C3-C8, an ASIA classification B-D, able to follow verbal instructions and commands, were able to sit upright with support if needed, and no history of or additional neurological impairment. Information regarding the participants icSCI (skeletal level, ASIA classification, date of injury, cause of injury) was obtained from clinicians and occupational therapists from their medical notes after informed consent was obtained.

Thirty two non-injured control participants comprised of sixteen young adults (mean age=23.6±4.54 years, 14 right handed) and sixteen older adults (Mean age=71±7.2 years, 12 right handed) from the local community. The inclusion criteria for non-injured control participants included; having no known or prior history of neurological or psychiatric disease, being able to understand and follow verbal instructions and being able to give written consent for themselves. The preferred limb (P) for participants with an icSCI was classified as the less impaired (LI) limb and was identified during the Chedoke Arm and Hand Activity Inventory (Barreca et al., 2004) (outlined below). The preferred limb of non-injured participants was determined as the limb that they perform daily tasks with, e.g. writing.

Table 5.0: Participants with icSCI characteristics.

Participant	Age (years, months)	Gender (M/F)	Time since icSCI (weeks)	Level of icSCI	Cause of icSCI	ASIA	More Impaired (MI limb)	CAHAI-9 (/63)
1	73.0	M	17	C6	Non-traumatic, C5/C6 cord compression	B	R	42
2	68.0	M	7	C5	Traumatic, Fall	D	L	60
3	67.0	M	17	C7	Traumatic, Fall	C	R	56
4	57.0	M	11	C8	Non-Traumatic, Spinal cord infarct at C5/C6	C	L	-
5	79.04	F	23	C6	Traumatic, Fall	D	L	62
6	69.06	M	8	C5/6	Traumatic, Fall	-	L	58
7	79.04	M	9	C5	Non-Traumatic, Cervical myelopathy	C	L	63
8	73.10	M	18	C3/4	Traumatic, Fall	C	R	52
9	65.10	M	15	C3-6	Traumatic, Fall	D	R	44

10	40.08	M	14	C6/7	Traumatic, Fall	D	L	63
11	65.04	M	14	C5	Traumatic, Fall	C	L	56
12	47.09	M	29	C5	Traumatic, Mountain Bike accident	D	L	63
13	56.10	M	21	C5	Non-Traumatic, Spinal abscess	C	L	-
14	45.02	M	6	C6	Traumatic, Mountain Bike accident	C	L	63
15	35.11	F	47	C4/5	Non-Traumatic, Spinal stroke	D	L	63
16	67.10	M	6	C4	Traumatic, Fall	D	L	63
17	86.06	M	10	C3/4	Non-Traumatic, Multilevel spinal cord degeneration	D	L	63
18	37.11	M	7	C4	Traumatic, Fall	D	L	63
Mean (SD)	61.61 (15.24)	M=16 F=2	18.28 (20.67)	C3/4=2,C4=2, C4/5=1,C5=5, C5/6=1,C6=3 C6/7=1,C7=1, C8=1,C3-6=1	Traumatic = 12 Non-Traumatic = 6	B=1 C=7 D=9	R=4 L=14	58.37 (6.90)

5.2.2 Ethical statement

Ethical approval for participants with an icSCI was gained from the Leeds (West) Research Ethics Committee (11/H1307/14) with additional site specific ethical approval gained from the North West Regional Spinal Injuries Centre. For the non-injured control participants ethical approval was gained from the Faculty of Biological Sciences Research ethics committee, University of Leeds (REF: BIOSCI 11-020). All participants in the study gave informed consent prior to inclusion within the study and the procedures conformed to the declaration of Helsinki.

5.3 Overview of data collection and analysis

For all participants quantitative analysis in the form of kinematics and surface electromyography (EMG) was undertaken and will be described below. For the participants with an icSCI additional analysis was obtained to gain further information regarding their ability to perform upper limb tasks such as reaching for objects.

5.3.1 Chedoke arm and hand activity inventory

The Chedoke arm and hand activity inventory (CAHAI) was developed by Barreca et al., (2004) in order to assess the degree to which the paretic limb participated in tasks. The full version of the CAHAI includes 13 tasks that are deemed to include gross and fine grasps and manipulation of objects of different sizes shapes and weights. It uses a seven point scale to determine the level of assistance needed to complete each task (1=total assistance, 7=complete independence). The CAHAI has three versions depending on the number of tasks used (CAHAI – 7, 9 and 13) and has been shown to be more sensitive to change in upper limb function than the Action Research Arm Test (ARAT) (Barreca et al., 2006). High inter-rater reliability (ICC = 0.98) and discrimination validity, by correlating shoulder pain with CAHAI, has been reported for the CAHAI (Barreca et al., 2005). The CAHAI has been validated twice in the SCI population to identify improvements in bimanual function after a bilateral training programme (Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2010). For the purpose of this study the CAHAI -9 was recorded as it involves nine bimanual tasks that are completed whilst sat at a height adjustable table. These included opening a coffee jar, dialling 999 on a telephone, pouring a glass of water, drawing a line with a ruler, drying their back with a towel, wringing out a washcloth, fastening five buttons on a vest, putting toothpaste on a toothbrush and cutting up medium resistance putty with a knife and fork. Each participant was scored by an occupational therapist on each task in the CAHAI-9. The CAHAI-9 was also used to identify the more impaired limb of each icSCI participant in the presence of the occupational therapist. The CAHAI-9 was carried out for all participants with an icSCI except one due to illness on the day of testing (although the more impaired limb was still identified by an occupational therapist for this participant).

5.3.2 Tasks

All participants (icSCI and non-injured) were sat in their wheelchair or chair at a height adjustable table so that their hips and knees were at ninety degrees, and so that the arms could be easily rested on the table without the need for trunk involvement. Participants were instructed to move from a standardised starting position to reach and grasp an object (unimanual) or objects (bimanual) using a precision grip (Stahl et al., 2014, Laffont et al., 2007), pick the object/s up and bring them back to the start position (all in the sagittal plane). The starting positions were at the edge of a height adjustable table with a 20cm distance between each limb. Participants were instructed to start each trial with their index finger and thumb touching. The object/s were also 20 cm apart. The task was self-paced and began with a verbal “go” command given by the experimenter. The task involved shoulder flexion, elbow extension, forearm supination and grasp formation using a precision grip. All participants had an opportunity to familiarise themselves with the task before data collection commenced. For all conditions the order of trials was pseudo-randomised (by object distance or size, see below) and the experimenter replaced the object/s before each trial.

5.3.2.1 Distance

When distance was manipulated the participants were instructed to reach and grasp object/s that were plastic blocks (3x3x1.8cm) and were placed at near (50% of maximal reach distance) or far (70% of maximal reach distance) locations in order to ensure enough difference in distance between the two conditions. Maximal reach distance for each participant was calculated as the maximum distance between the edge of the height adjustable table and where each participant could reach with their fingertips (of both arms) on the table, while sitting at the height adjustable table with both arms fully extended and their back against the chair/wheelchair. In previous studies within the cSCI population the distance at which the object was placed has varied between studies e.g. some studies used maximum arm length to decipher the object location and some used set distances such as 20cm (Mateo et al., 2015) making it difficult for cross-comparison between studies. In the current thesis it was decided that calculating distance as a function of each individual's arm length would be beneficial as following cSCI the ability to extend the arm is often reduced due to paralysis of the triceps brachii (Robinson et al., 2010).

The unimanual distance study (chapter 6) comprised of four blocks of eight unimanual trials; Preferred/Less Impaired (P/LI) Near, P/LI Far, Non-preferred/More Impaired (NP/MI) Near, NP/MI Far and the bimanual distance study (chapter 7) comprised of four blocks of eight bimanual trials, two symmetrical blocks; P/LI and NP/MI limbs Near (NN), P/LI and NP/MI limbs Far (FF) and two asymmetrical blocks; P/LI Near NP/MI Far (NF) and P/LI Far NP/MI Near (FN).

5.3.2.2 Size

For the size study there was also eight blocks of eight trials all performed at the near object distance so not to manipulate object size and object distance at the same time. The different object/s used were plastic blocks either 3x3x1.8cm (small) or 6x3x1.8cm (large) (Paulignan et al., 1997). The four blocks of unimanual trials in study one (chapter 6) included; P/LI Small (same as P/LI Near), P/LI Large, NP/MI Small (same as NP/MI Near), NP/MI Large and the four blocks of bimanual trials in study two (chapter 7) included two symmetrical blocks; P/LI Small NP/MI Small (SS, same as P/LI Near NP/MI Near (NN)), P/LI Large NP/MI Large (LL) and two asymmetrical blocks; P/LI Small NP/MI Large (SL) and P/LI Large NP/MI Small (LS). Four of the eighteen participants with an icSCI could not complete the size aspect of the study, due to a reduction in their ability to open their hand to a large enough aperture in order to grasp the object.

5.3.3 Kinematic system

A five camera motion analysis system (Proreflex, Qualisys, Sweden) was used to collect three dimensional data of the upper limbs in all participants at a sampling rate of 120Hz. This motion capture system produces accurate 3D data by tracking reflective markers placed onto the skin. The markers reflect infrared light from the camera flashes and provide X, Y, Z coordinate values throughout the movement of the upper limbs. Reflective markers were placed on the upper limbs at the following positions; right and left medial wrist (12.7mm), right and left index finger and the right and left thumb (9.5mm). The markers were placed at these positions on bony prominences to help reduce the effect of skin movement and to ensure that marker placement was consistent between participants. An additional marker was also placed on the object for purpose of analysis. A five camera set up was used to avoid occlusion of markers by the body, which can have significant impact on the overall performance of the motion capture system (Chen and Davis, 2000). The cameras were placed in a semi-circular arrangement around the height adjustable table and placed in order to prevent any two cameras facing each other directly. To ensure that the 3D data collected was accurate the system was calibrated before any data collection took place. For the present studies both dynamic and static calibration was used. This included a calibration frame consisting of 4 markers and a calibration wand consisting of two markers so that the space in which the upper limb movement was taking place could be defined and positions of the reflective markers could be calculated by direct linear transformation. In addition the focus and aperture of each camera was checked before data collection commenced to ensure that each marker could be distinguished.

5.3.3.1 Kinematic data analysis

The data collected by the motion capture system was transferred to a Windows-based data acquisition software (Qualisys track manager) where the reflective markers were identified and labelled. This was then exported and analysed via Visual3D where it was filtered using a low-pass Butterworth filter with a cut-off frequency of 10Hz (Paulignan et al., 1997, Bootsma et al., 1994) to remove any noise from the data collected. Once filtered, Visual3D was used to obtain the following dependent variables.

5.3.3.2 Kinematic dependent variables

Dependent variables were computed in line with previous research (Mateo et al., 2013, Coats and Wann, 2011, de los Reyes-Guzman et al., 2010, Balasubramanian et al., 2012, Trombly and Wu, 1999, Cacho et al., 2011, Steenbergen and Van Der Kamp, 2004). Onset of the movement was defined when the velocity of the wrist reached 50mm/s. Following this, movement end was determined using the marker placed on the object and defined as the moment at which the velocity of this marker increased in z direction (i.e. object lift). Movement time (MT) was calculated as the duration between movement onset and movement endpoint, and peak velocity (PV) of the wrist marker corresponded to the maximal velocity. MT was further investigated by calculating the percentage of MT spent decelerating (propDT); the time between PV and the end of movement divided by MT. Then the percentage of MT spent in a final adjustment phase (FAP), which was the time between the velocity of the wrist reaching 50 mm/s during the deceleration phase and the end of the movement divided by total MT (propFAP). Movement smoothness was examined using the number of zero-crossings (Steenbergen and Van Der Kamp, 2004) in the acceleration profile of the approach phase (PV to start of FAP) and final adjustment phase (start of FAP to END). Resultant path length was calculated as the total resultant distance travelled by the wrist marker between the start and end of the movement. Path length in the vertical direction (z) was also calculated to identify differences in wrist height between groups (de los Reyes-Guzmán et al., 2010).

For the calculation of the grasp component, grasp aperture was quantified using the resultant distance between the markers on the thumb/s and index finger/s of each hand. Maximum grasp aperture (MGA); the largest distance between the index finger and thumb during the reach was calculated as was the time at which this occurred during MT (expressed as a percentage of total MT).The coupling between the transport and grasp phases (TrG) was calculated by identifying the time of peak deceleration minus the time of maximum grasp aperture (MGA), a smaller value indicated greater coupling.

To examine bimanual (interlimb) coordination synchronicity of the two limbs was examined at movement onset, PV, start of FAP and movement endpoint (Coats and Wann, 2012, Mason and Bruyn, 2009). This was calculated as the absolute difference in time between the P/LI and NP/MI limbs when reaching these kinematic parameters.

5.3.3.3 Kinematic statistical analysis

To examine the differences with respect to transport and grasp phase kinematics intraindividual means (of the eight trials) were computed for both hands, for every dependent variable, for each participant in all conditions. The data was then entered into separate mixed repeated measures ANOVA's to examine the main effects of group (between subjects variable - icSCI, YA, OA), distance or size (within subjects variable - unimanual N, F or S, L, bimanual NN, FF, NF, FN or SS, LL, SL, LS) and limb (within subjects variable - P/LI, NP/MI) (see each study for further details, chapters 6, 7 and 8). To investigate interlimb synchrony a series of repeated measures ANOVAs were performed to permit the exploration of the main effect of group and distance (NN, FF, NF, FN) or size (SS, LL, SL ,LS). For all dependent variables, when the sphericity assumption was violated F and P values generated using the Greenhouse-Geisser correction are reported. For the repeated-measures ANOVAs effect sizes were calculated with small, medium, and large effect sizes being indicated by 0.1, 0.25, and 0.4 (Cohen, 1988). When significant main effects were found ($p<0.05$), means were compared post hoc using pairwise comparisons with Bonferonni adjustments and all significant interactions were explored using the appropriate inferential statistics.

5.3.4 Surface Electromyography

Muscle activity was measured using the Noraxon Telemyo 2400T with G2 miniature wireless receiver EMG system testing at 1500 Hz, which was synced with the Proreflex Motion Capture System using an external trigger. Standard surface electrodes were used and the skin was prepped using alcohol based swabs and Nu-Prep skin preparation gel to prevent any resistance. Electrodes were placed on the anterior deltoid, biceps brachii, lateral head of the triceps brachii and the extensor digitorum superficialis. These muscles were chosen as the anterior deltoid flexes the shoulder in order to extend the arm forward, the biceps brachii and triceps are an agonist-antagonistic pair involved in extension and flexion of the elbow and the extensor digitorum superficialis extends the fingers to form maximum grasp aperture as the upper limb moves towards the object. Additionally, these muscles chosen are representative of icSCI to C5-C8 and have shown differing levels of paresis depending on the level of the iSCI (Janssen-Potten et al., 2008, Mateo et al., 2015). The electrodes were placed parallel to the direction of the muscle fibres and activity of the muscles was checked prior to data collection to ensure correct electrode placement i.e. the triceps were checked using extension of the elbow and biceps using flexion of the elbow. For seven of the participants (four participants with an icSCI and three older adults) in the thesis there is missing EMG data due to technical difficulties (n=3) or not consenting to EMG being recorded (n=4).

5.3.4.1 Surface Electromyography data analysis

Once collected the data was exported from Qualisys track manager to Visual 3D where it was filtered to remove any noise from the data using a high-pass filter with a cut off frequency of 20Hz and a low-pass filter with a cut off frequency of 5Hz (Bonnefoy et al., 2009). It was then rectified in order to make the signal absolute and timing of peak muscle activity was identified for each muscle and each limb for each participant. Following this, the time difference between timing of peak muscle activity and timing of kinematic events (movement onset, time of PV, start of FAP and the end of the movement) was calculated. This was to establish muscle patterns throughout the reach to grasp movement, which to my knowledge has not been investigated within the icSCI population. A negative value indicated that the peak muscle activity occurred before the kinematic event and a positive value indicated that the peak muscle activity occurred after the kinematic event. Finally, the time difference between the time of peak triceps brachii activity (agonist) and lowest biceps brachii activity (antagonist) was quantified to assess the agonist-antagonistic muscle activity during the reach to grasp movement. This may be weaker in participants with an icSCI due to paralysis of the triceps brachii and biceps brachii and increased reliance on other muscles, such as the shoulder complex, in order to extend the elbow (Koshland et al., 2005).

5.3.4.2 Surface electromyography statistical analysis

Once computed data were entered into mixed repeated measures ANOVA's to examine the main effects of group (between subjects variable - icSCI, YA, OA), distance or size (within subjects variable - unimanual N, F or S, L, bimanual NN, FF, NF, FN or SS, LL, SL, LS) and limb (within subjects variable - P/LI, NP/MI) (see each study for further details, chapters 6, 7 and 8). For all dependent variables, when the sphericity assumption was violated F and P values generated using the Greenhouse-Geisser correction are reported. When significant main effects were found ($p<0.05$), means were compared post hoc using pairwise comparisons with Bonferonni adjustments and all significant interactions were explored using the appropriate inferential statistics. For the repeated-measures ANOVAs effect sizes were calculated with small, medium, and large effect sizes being indicated by 0.1, 0.25, and 0.4 (Cohen, 1988).

Chapter 6 Study one

6.1 Introduction

Regaining arm and hand function is a rehabilitative priority for individuals with a cSCI (Anderson, 2004, Snoek et al., 2004), however, the research quantifying the behavioural control of arm and hand movements after cSCI is lacking when compared to research based on lower limb function. This information is important in order to guide potential rehabilitation paradigms to improve arm and hand function. To date the limited literature suggests that unimanual movements are slower (longer duration and lower peak velocity) and less smooth than non-injured individuals (Mateo et al., 2015), with evidence for novel muscle patterns due to muscle paralysis in the upper limb (Koshland et al., 2005, Jacquier-Bret et al., 2009, Janssen-Potten et al., 2008) (see chapter 4, section 4.2 for more detail).

In the non-injured population a body of research has focused on how object distance and object size influence reach to grasp kinematics and EMG in order to understand control of the upper limb (see chapter 3, sections 3.2.1 and 3.2.2 for further details). However, limited research has been undertaken to investigate how these object properties influence prehension after cSCI, despite evidence for a decrease in functional workspace (Robinson et al., 2010) and reduced hand opening (Stahl et al., 2014).

The current study comprises two experiments which aim to quantify how unimanual prehension changes after icSCI, and how this compares to non-injured younger adults (YA) and older adults (OA). The latter group is considered important for inclusion firstly because of the recently documented aging SCI population (Thompson et al., 2014). In addition, obvious differences between OA and YA have already been noted in previous prehension studies (see chapter 3, section 3.2.5) (Seidler-Dobrin and Stelmach, 1998, Goggin and Stelmach, 1990, Coats and Wann, 2011). The first experiment aims to examine the effects of object distance on unimanual prehension and the second experiment aims to investigate how object size influences unimanual prehension. The study tests the following hypotheses; (1) participants with an icSCI will display longer (duration), slower (lower peak velocity), less smooth movements than non-injured control participants (Mateo et al., 2015), (2) participants with an icSCI will display novel muscle patterns (in terms of timing of peak muscle activity) when compared to non-injured control participants due to muscle paralysis (Koshland et al., 2005), (3) object distance and object size will influence kinematic parameters in agreement with previous research in non-injured adults, e.g. the farther the object distance and smaller the object the longer the movement time due to increase in task difficulty (Bootsma et al., 1994).

6.2 Methods

6.2.1 Participants

Eighteen participants (table 5.0) with an icSCI (Mean age=61.61 ±15.24 years, 14 right handed), sixteen younger adults (Mean age=23.6±4.54 years, 14 right handed) and sixteen older adults (Mean age=71±7.2 years, 12 right handed) volunteered for participation in this study. Further details can be found in chapter 5 (section 5.2.1).

6.2.2 Task

All details regarding the specifics of the task are presented in chapter 5 (section 5.3.2). As experiment one was concerned with object distance the objects (3x3x1.8cm) were placed at 50% (near) and 70% (far) of each participant's maximal reach distance. Therefore there were four blocks of eight trials for experiment one (figure 6.0 a and b); Preferred/Less Impaired limb (P/LI) Near, Non-preferred/More Impaired limb (NP/MI) Near, P/LI limb Far and NP/LI limb Far. As experiment two was concerned with object size (small and large) the objects were placed at the near distance so not to manipulate both object distance and object size in the same instance. Therefore there were four blocks of eight trials for experiment two; P/LI Small, NP/MI Small, P/LI Large, NP/MI Large.

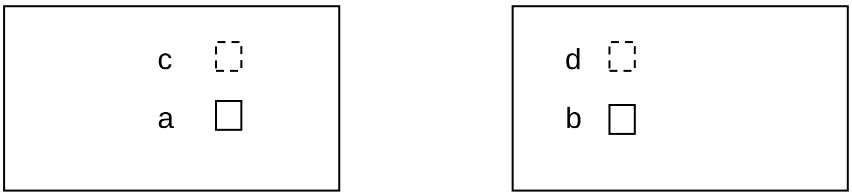

Figure 6.0: Drawn depiction of the experimental set up. (Four blocks of unimanual trials in experiment one; P/LI Near (a), NP/MI Near (b), P/LI Far (c), NP/MI Far (d) if the P/LI limb is right)

6.2.3 Dependent variables and statistical analysis

A full description of procedures for the kinematic and EMG analyses, in addition to the dependent variables is presented in chapter 5 (sections 5.3.3 and 5.3.4). To analyse the kinematic and EMG data statistically, a series of repeated measures

ANOVA's were performed for each dependent variable. This analyses permitted exploration of the main effects of group (3 – icSCI, YA, OA), distance (2 – Near, Far) and limb (2 – P/LI, NP/MI) for experiment one and group (3 – icSCI, YA, OA), size (2 – small, large) and limb (2 – P/LI, NP/MI) for experiment two. In order to investigate a limb by group interaction distance or size was collapsed and two one-way ANOVAs (one for each limb) were performed to determine any significant group differences. Following this, paired t-tests were performed to determine whether there was a significant difference between limbs for each group. In the event of a distance by group interaction or size by group interaction limb was collapsed and paired t-tests were performed to investigate whether a significant difference between near and far/small and large conditions emerged for each group. Subsequently one-way ANOVAs for each condition, e.g. near or far distance, were performed to determine any significant differences between groups.

6.3 Results for experiment one - Kinematic Data

6.3.1 Movement time

As can be seen in figure 6.1a participants with an icSCI (Mean (M) =1519ms) produced movements of a longer duration than YA (M=712ms) and OA (M=849ms) [$F(2,41)=29.09$, $p<0.001$, $\eta^2=0.59$] with no significant difference between YA and OA. There was no significant main effect of distance [$F(1,41)=0.72$, $p>0.05$, $\eta^2=0.02$] but a significant main effect of limb emerged [$F(1,41)=6.84$, $p<0.05$, $\eta^2=0.14$] as the NP/MI limb (M=1077ms) made movements of a longer duration than the P/LI limb (M=976ms).

A significant limb by group interaction emerged [$F(2,41)=6.73$, $p<0.01$, $\eta^2=0.25$] and subsequent one-way ANOVAs (distance collapsed) for each limb were performed. For the P/LI limb [$F(2,49)=20.78$, $p<0.001$, $\eta^2=0.47$] and NP/MI limb [$F(2,49)=23.21$, $p<0.001$, $\eta^2=0.50$] a significant group difference arose as participants with an icSCI (LI=1347ms, MI=1633ms) produced a longer movement time than YA (P=729ms, NP=706ms) and OA (P=847ms, NP=869ms). Paired t-tests (to determine differences between limb) revealed that a significant difference between the limbs only occurred for the participants with an icSCI [$t(17)=2.40$, $p<0.05$] as movement time for the MI limb (M=1633ms) was longer than the LI limb (M=1347ms). There was no significant difference between limbs for YA [$t(15)=1.11$, $p>0.05$] or OA [$t(15)=-0.81$, $p>0.05$].

6.3.2 Peak velocity

There was a significant main effect of group (figure 6.1b) [$F(2,41)=13.35$, $p<0.001$, $\eta^2=0.40$] as participants with an icSCI (M=568mm/s) reached a lower peak velocity than YA (M=847mm/s) and OA (M=709mm/s). In addition, the YA reached a significantly greater PV than OA. A significant main effect of distance also emerged [$F(1,41)=223.57$, $p<0.001$, $\eta^2=0.85$] with greater PV when reaching to the far (M=805mm/s) than near object (M=611mm/s). There was no significant main effect of limb [$F(1,41)=0.40$, $p>0.05$, $\eta^2=0.01$].

A significant distance by group interaction occurred [$F(2,41)=7.12$, $p<0.01$, $\eta^2=0.26$] and the results of the subsequent paired t-tests (limb collapsed) revealed a significant difference in PV between near (icSCI=504mm/s, YA=711mm/s, OA=608mm/s) and far (icSCI=624mm/s, YA=962mm/s, OA=802mm/s) conditions for each group of participants (icSCI [$t(17)=-5.54$, $p<0.001$], YA [$t(15)=-12.12$, $p<0.001$] and OA [$t(15)=-10.38$, $p<0.001$]). One-way ANOVAs for each object distance revealed that when reaching to the near object there was a significant group difference [$F(2,49)=11.58$, $p<0.001$, $\eta^2=0.33$] as participants with an icSCI (M=504mm/s) reached a lower PV than YA (M=711mm/s). However, there was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). When reaching for the far object there was also a significant group difference [$F(2,49)=16.77$, $p<0.001$, $\eta^2=0.42$] as participants with an icSCI (M=624mm/s) reached a lower PV than both YA (M=962mm/s) and OA (M=802mm/s). Additionally, the OA reached significantly lower PV than YA ($p<0.05$).

6.3.3 Proportion of movement time spent decelerating

Participants with an icSCI (M=71.15%) spent a longer proportion of movement time decelerating (propDT) compared to YA (M=58.21%) and OA (M=65.05%) [$F(2,41)=17.73$, $p<0.001$, $\eta^2=0.43$] (figure 6.1c). There was also a significant difference between YA and OA ($p<0.05$). There was no significant main effect of limb [$F(1,41)=0.05$, $p>0.05$, $\eta^2=0.001$], but a significant main effect of distance [$F(1,41)=4.88$, $p<0.01$, $\eta^2=0.11$] showed that a longer proportion of movement time was spent decelerating towards the near object (M=65.84%) than the far object (M=63.76%).

A significant limb by group interaction [$F(2,41)=5.06$, $p<0.05$, $\eta^2=0.92$] emerged and subsequent one-way ANOVAs (distance collapsed) revealed that for the P/LI limb there was a significant difference between groups [$F(2,49)=6.62$, $p<0.01$, $\eta^2=0.22$] as participants with an icSCI (M=68.19%) spent a longer proportion of movement time decelerating compared to YA (M=58.69%). There was no significant difference between participants with an icSCI and OA but a significant difference emerged between YA and OA (M=67.10%, $p<0.05$). For the NP/MI limb there was also a significant difference between groups [$F(2,49)=3.62$, $p<0.05$, $\eta^2=0.13$] as participants with an icSCI (M=70.12%) spent a longer proportion of time decelerating compared to YA (M=59.10%). There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). Paired t-tests revealed that no significant difference in propDT emerged between the P/LI and NP/MI limb for participants with an icSCI [$t(17)=-0.46$, $p>0.05$], YA [$t(15)=-0.38$, $p>0.05$] or OA [$t(15)=1.67$, $p>0.05$].

6.3.4 Proportion of movement time spent in the final adjustment phase

Figure 6.1d shows that participants with an icSCI (M=28.42%) produced a greater proportion of movement time in the final adjustment phase (propFAP) than YA (M=9.39%) and OA (M=15.04%), with no significant difference between YA and OA ($p>0.05$) [$F(2,42)=7.94$, $p<0.01$, $\eta^2=0.27$]. There was a significant main effect of distance [$F(1,42)=16.99$, $p<0.001$, $\eta^2=0.29$] due to a longer propFAP when reaching to the near object (M=19.32%) compared to far object (M=15.90%). No significant main effect of limb [$F(1,42)=2.59$, $p>0.05$, $\eta^2=0.06$] or significant interactions emerged.

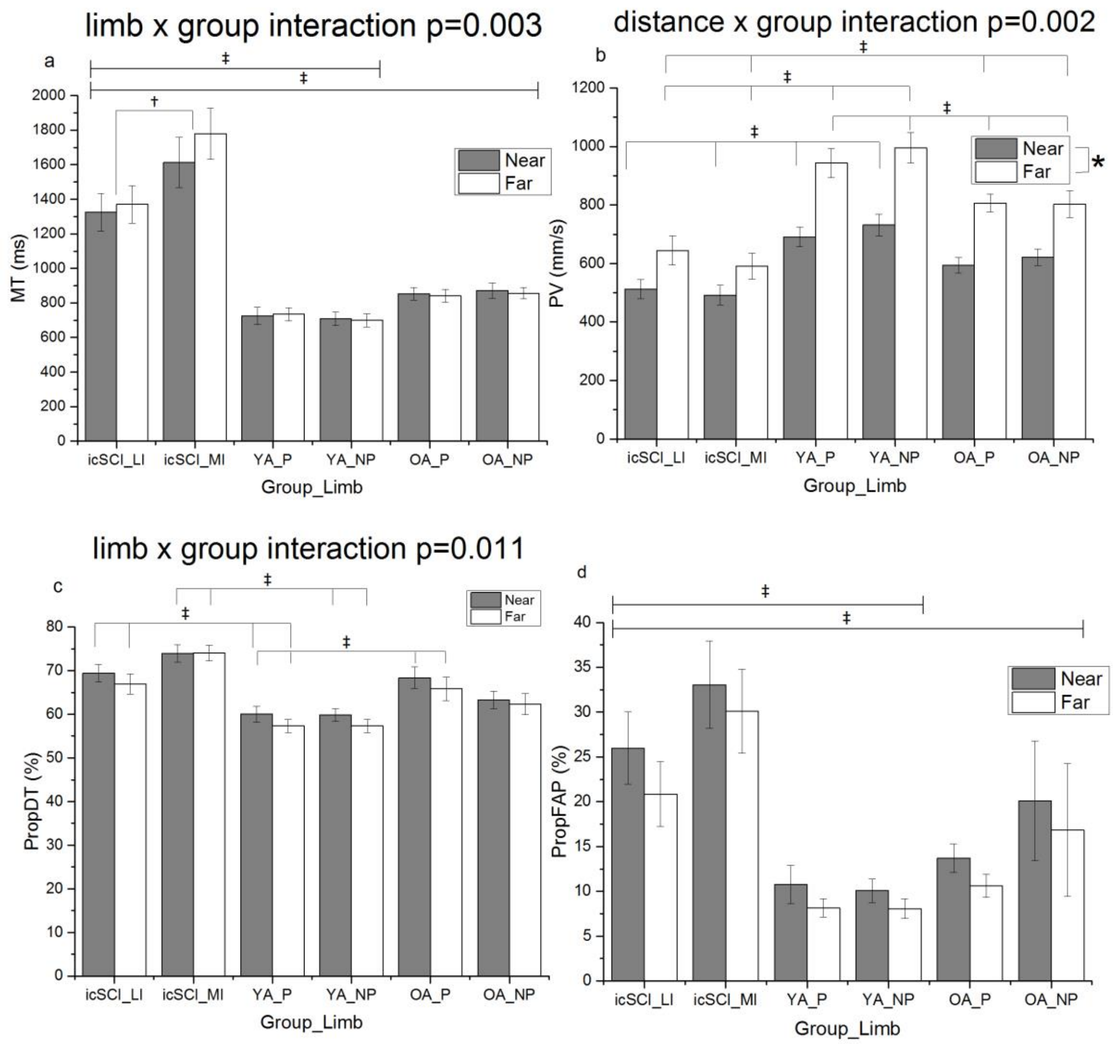

Figure 6.1: Group and limb means (±standard error) for movement time (MT) (a), peak velocity (PV) (b), proportion of movement time spent decelerating (propDT) (c) and proportion of movement time spent in the final adjustment phase (propFAP) (d) for near (grey) and far (white) conditions (* denotes significant difference between near and far distances, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.3.5 Number of adjustments in the approach phase

A significant main effect of group emerged [$F(2,41)=44.05$, $p<0.001$, $\eta^2=0.68$] as participants with an icSCI (M=3.246) made more adjustments than YA (M=0.34) and

OA ($M=1.063$) (figure 6.2a). There was no significant main effect of distance [$F(1,41)=1.91$, $p>0.05$, $\eta^2=0.05$] or limb [$F(1,41)=3.53$, $p>0.05$, $\eta^2=0.08$] but a significant limb by group interaction emerged [$F(2,41)=5.17$, $p<0.05$, $\eta^2=0.20$].

To investigate the significant limb by group interaction subsequent one-way ANOVAs (distance collapsed) revealed that for the P/LI limb [$F(2,49)=19.02$, $p<0.001$, $\eta^2=0.45$] and NP/MI [$F(2,49)=22.50$, $p<0.001$, $\eta^2=0.49$] participants with an icSCI (LI=2.55, MI=4.39) produced more adjustments than YA (P=0.36, NP=0.33) and OA (P=1.12, NP=1.06). Paired t-tests revealed that the MI ($M=4.39$) limb made significantly more adjustments than the LI ($M=2.55$) limb for participants with icSCI [$t(17)=-2.40$, $p<0.05$]. There was no significant difference between the limbs for YA [$t(15)=0.33$, $p>0.05$] or OA [$t(15)=0.27$, $p>0.05$].

6.3.6 Number of adjustments in the final adjustment phase

A significant main effect of group [$F(2,42)=13.73$, $p<0.001$, $\eta^2=0.40$] occurred as participants with an icSCI ($M=5.28$) produced significantly more adjustments than YA ($M=0.83$) and OA ($M=1.27$) (figure 6.2b). There was no significant difference between YA and OA ($p>0.05$). There was a significant main effect of distance [$F(1,42)=24.26$, $p<0.001$, $\eta^2=0.37$] as more adjustments were made to the near object ($M=2.80$) than far object ($M=2.11$), and a significant main effect of limb also emerged [$F(1,42)=6.02$, $p<0.05$, $\eta^2=0.13$] as more adjustments were made by the NP/MI limb ($M=2.87$) than P/LI limb ($M=2.05$).

There was a significant distance by group interaction [$F(2,42)=4.95$, $p<0.05$, $\eta^2=0.19$] and subsequent paired t-tests (limb collapsed) revealed that there was significantly more adjustments made when reaching to the near object (icSCI=5.26, OA=1.51) compared to the far object (icSCI=4.34, OA=1.03) for both participants with an icSCI [$t(17)=2.47$, $p<0.05$] and OA [$t(15)=3.63$, $p<0.01$], but not for the YA [$t(15)=2.05$, $p>0.05$]. One-way ANOVAs revealed for the near object [$F(2,49)=12.63$, $p<0.001$, $\eta^2=0.35$] and far object [$F(2,49)=11.76$, $p<0.001$, $\eta^2=0.33$] there was a significant group difference as participants with an icSCI (Near=5.26, Far=4.34) produced more adjustments than YA (Near=0.98, Far=0.72) and OA (Near=1.51, Far=1.03).

Additionally, a significant limb by group interaction emerged [$F(2,42)=8.15$, $p<0.01$, $\eta^2=0.13$] and subsequent one-way ANOVAs (distance collapsed) revealed that for the P/LI limb [$F(2,49)=8.50$, $p<0.01$, $\eta^2=0.27$] and the NP/MI limb [$F(2,49)=14.20$, $p<0.001$, $\eta^2=0.38$] participants with an icSCI (LI=3.56, MI=6.20) made significantly more adjustments than YA (P=0.93, NP=0.76) and OA (P=1.31, NP=1.23). Paired t-tests also revealed that a significant difference between the MI (M=3.56) and LI (M=6.20) limb occurred for the participants with an icSCI [t(17)=-3.15, p<0.01) but there was no significant difference between limbs for the YA [t(15)=1.17, p>0.05] or OA groups [t(15)=0.73, p>0.05].

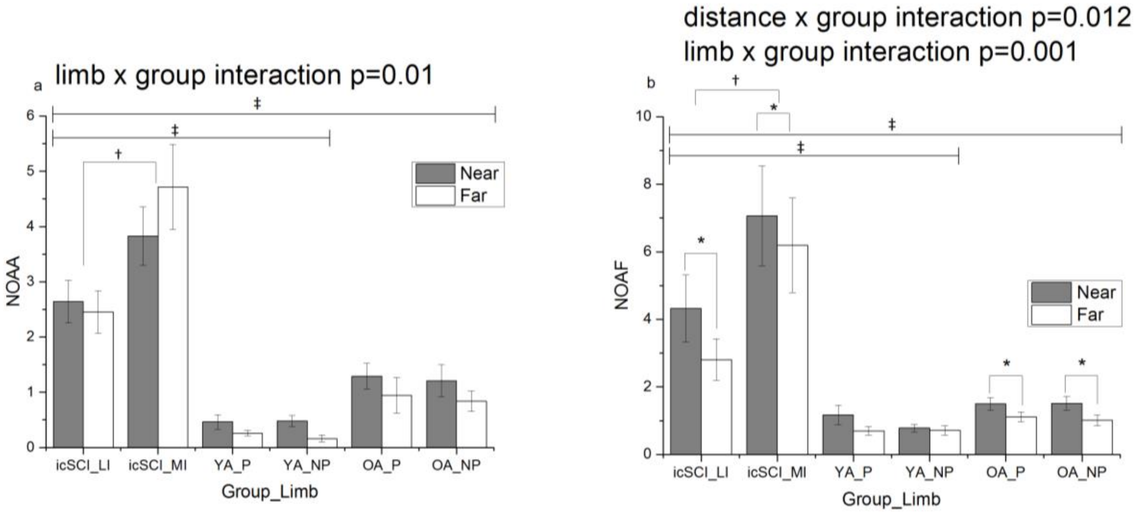

Figure 6.2: Group and limb means (±standard error) for number of adjustments in the approach phase (NOAA) (a) and number of adjustments in the final adjustment phase (NOAF) (b) in near (grey) and far (white) conditions. (* denotes significant difference between near and far distances, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.3.7 Maximum grasp aperture

No significant main effects of group [F(2,41)=0.89, p>0.05, η^2=0.04], distance [F(1,41)=0.22, p>0.05, η^2=0.01] or limb [F(1,41)=0.01, p>0.05, η^2=0.001] were yielded, as seen in figure 6.3a. However, a significant distance by group interaction emerged [F(2,41)=3.25, p<0.05, η^2=0.14].

To explore the distance by group interaction subsequent paired t-tests (limb collapsed) revealed that there was a significant difference in MGA when reaching for both the near (icSCI=9.69cm, OA=9.19cm) and far object (icSCI=9.37cm, OA=9.36cm) for the participants with an icSCI [$t(17)=2.11$, $p<0.05$] and OA [$t(15)=-2.12$, $p<0.05$] but not for the YA [$t(15)=-1.12$, $p>0.05$]. Interestingly for the participants with an icSCI MGA was greater when reaching for the near object but for OA it was greater when reaching for the far object. One-way ANOVAs showed that for the near object there was a significant group difference [$F(2,49)=3.99$, $p<0.05$, $\eta^2=0.20$] as participants with an icSCI (M=9.69cm) produced a greater MGA than YA (M=9.08cm). When reaching for the far object there was no significant group difference [$F(2,49)=0.37$, $p>0.05$, $\eta^2=0.001$].

6.3.8 Time of maximum grasp aperture as a percentage of movement time

As shown in figure 6.3b a significant main effect of group arose [$F(2,41)=8.69$, $p<0.01$, $\eta^2=0.30$] as participants with an icSCI (M=70.40%) reached MGA significantly earlier than YA (M=55.77%). There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). There was also a significant main effect of distance [$F(1,41)=16.15$, $p<0.001$, $\eta^2=0.28$] as MGA was reached significantly earlier when reaching to the near object (M=61.22%) compared to the far object (M=65.16%). No significant main effect of limb [$F(1,41)=0.28$, $p>0.05$, $\eta^2=0.01$] or significant interactions emerged.

6.3.9 Transport and grasp coupling

There was a significant main effect of group (figure 6.3c) [$F(2,41)=14.21$, $p<0.001$, $\eta^2=0.41$] as participants with an icSCI (M=257ms) produced less coupled transport and grasp phases than YA (M=46ms) and OA (M=72ms). There was no significant difference between YA and OA ($p>0.05$). A significant main effect of distance emerged [$F(1,41)=6.82$, $p<0.05$, $\eta^2=0.14$] as transport and grasp coupling to the far object (M=-153ms) was less coupled than when moving to the near object (M=-97ms). No significant main effect of limb [$F(1,41)=0.46$, $p>0.05$, $\eta^2=0.01$] or significant interactions emerged.

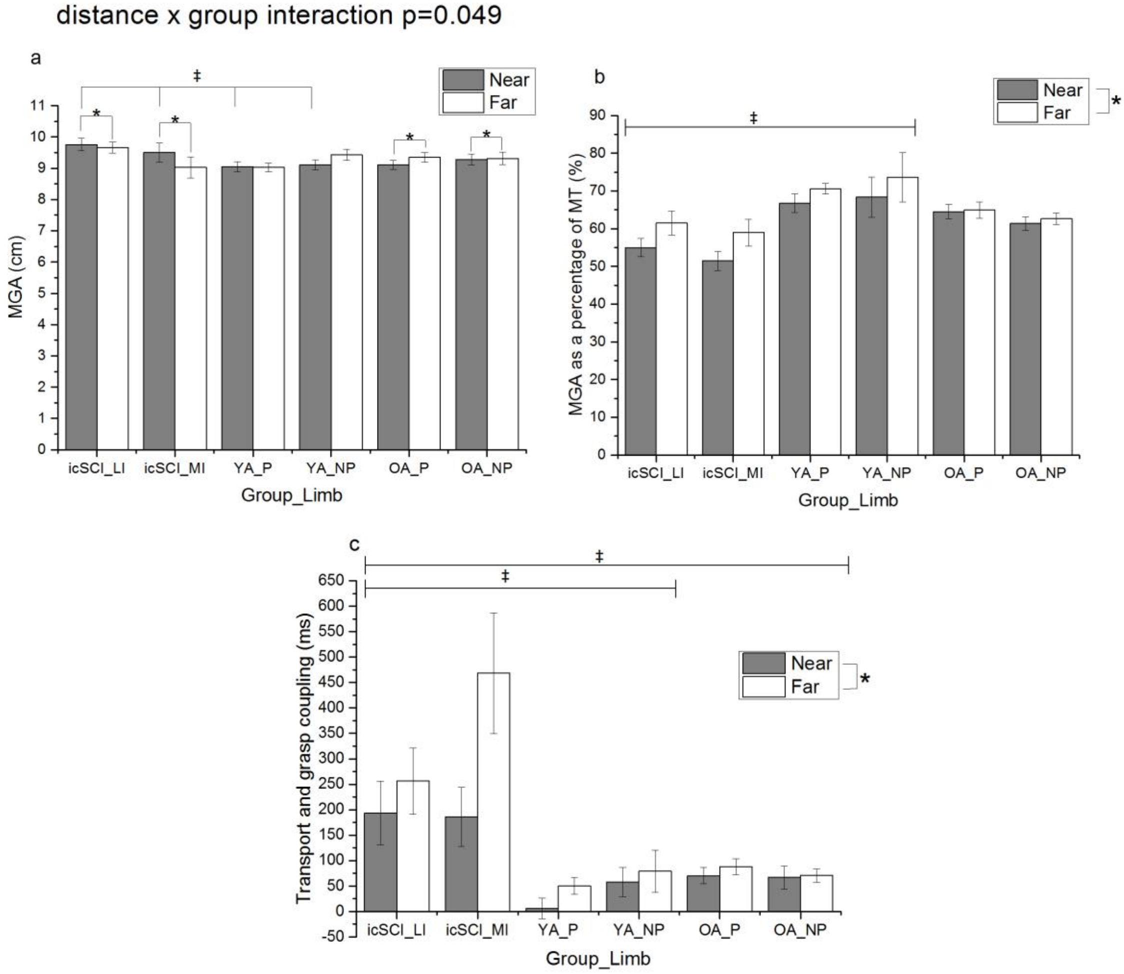

Figure 6.3: Group and limb means (±standard error) for maximum grasp aperture (MGA) (a), time of maximum grasp aperture as a percentage of movement time (MGA as a percentage of MT) (b) and transport and grasp coupling (c) in near (grey) and far (white) conditions. (* denotes significant difference between near and far distances, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.3.10 Path length

Participants with an icSCI (M=33.5cm) produced movements with a longer resultant path length than OA (M=27.2cm) [$F(2,40)=4.39$, $p<0.05$, $\eta^2=0.18$] (figure 6.4a) with no significant difference emerging between participants with an icSCI and YA or YA and OA (p>0.05). A significant main effect of distance emerged [F(1,40)=175.31, p<0.001, η^2=0.91] because as expected path length was longer to the far object (M=33.9cm) than the near (M=26.1cm) object. The main effect of limb [F(1,40)=0.25, p>0.05, η^2=0.01] did not reach significance and no significant interactions emerged.

With regards to total path length in the vertical direction (z) there was no significant main effect of group [F(2,42)=2.21, p>0.05, η^2=0.10], distance [F(1,42)=5.52, p>0.05, η^2=0.12] or limb [F(1,42)=0.45, p>0.05, η^2=0.01] and no significant interactions emerged (figure 6.4b). However, participants with an icSCI (M=19.7cm) produced a greater maximum wrist height than YA (M=11.8cm) [F(2,42)=5.24, p<0.01, η^2=0.20], but no significant difference emerged between participants with an icSCI and OA or YA and OA (p>0.05) (figure 6.4c). For maximum wrist height there was no significant main effect of distance [F(1,42)=3.28, p>0.05, η^2=0.07] or limb [F(1,42)=0.97, p>0.05, η^2=0.02] and no significant interactions emerged.

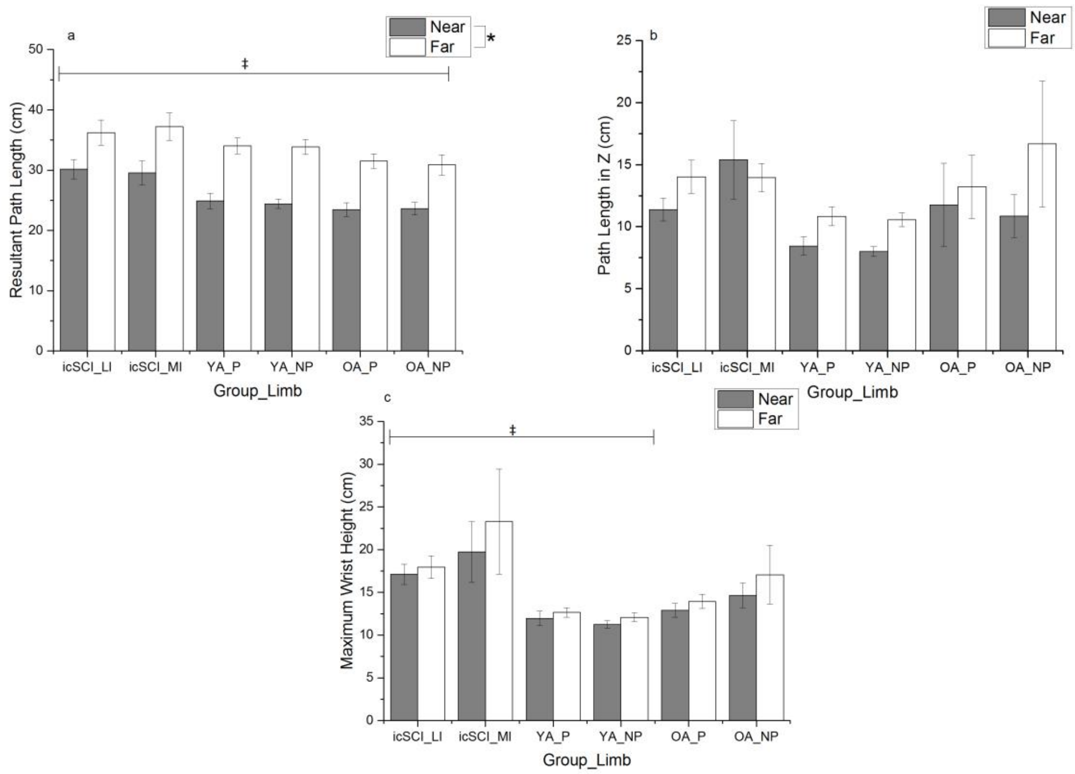

Figure 6.4: Group and limb means (±standard error) for resultant path length (a), path length in the vertical direction (z) (b) and maximum wrist height (c) in near (grey) and far (white) conditions. (* denotes significant difference between near and

far distances, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.4 Electromyography analysis

For the timing of peak muscle activity in relation to kinematic events it is clear from table 6.0 that for all participants this occurs between peak velocity and the start of the final adjustment phase (an example of a kinematic profile and EMG profile for a participant with an icSCI and a YA is presented in figure 6.5a-d). Therefore this was the focus of the subsequent statistical analyses.

6.4.1 Anterior Deltoid

YA (M=-3ms) produced peak anterior deltoid activity closer to the time of peak velocity [$F(2,34)=41.70$, $p<0.001$, $\eta^2=0.71$] when compared to OA (M=267ms) and participants with an icSCI (M=574ms), but OA reached peak anterior deltoid activity closer to time of PV compared to participants with an icSCI. In addition, participants with an icSCI (M=-96ms) and OA (M=-173ms) produced peak anterior deltoid activity closer to the start of final adjustment phase when compared to YA (M=-357ms) [$F(2,34)=11.89$, $p<0.001$, $\eta^2=0.41$]. In relation to PV and start of FAP there was no significant main effect of distance (PV [$F(1,34)=0.47$, $p>0.05$, $\eta^2=0.01$], FAP [$F(1,34)=0.02$, $p>0.05$, $\eta^2=0.001$]) or limb (PV [$F(1,34)=0.11$, $p>0.05$, $\eta^2=0.003$], FAP [$F(1,34)=0.68$, $p>0.05$, $\eta^2=0.02$]) and no significant interactions emerged.

6.4.2 Biceps Brachii

YA (M=3ms) produced peak biceps brachii activity closer to the time of PV compared to participants with an icSCI (M=463ms) and OA (M=219ms) [$F(2,34)=10.07$, $p<0.001$, $\eta^2=0.54$], while OA produced peak biceps brachii activity closer to PV than participants with an icSCI. Although not significant, participants with an icSCI (M=-206ms) produced peak biceps brachii activity closer to the start of FAP that YA (M=-351ms) [$F(2,34)=2.58$, $p>0.05$, $\eta^2=0.13$]. There was a significant main effect of limb in relation to PV [$F(1,34)=4.25$, $p<0.05$, $\eta^2=0.11$] and start of FAP [$F(1,34)=12.69$, $p<0.01$, $\eta^2=0.27$] as the P/LI limb produced peak biceps brachii activity closer to the start of FAP (P/LI limb=-209ms, NP/MI limb= -309ms) and the NP/MI produced biceps brachii activity closer to PV (NP/MI limb = 198ms, P/LI limb

= 258ms). There was no significant main effect of distance in relation to PV [$F(1,34)=0.006$, $p>0.05$, $\eta^2=0.001$] or the start of FAP [$F(1,34)=0.80$, $p>0.05$, $\eta^2=0.02$] and no significant interactions emerged.

6.4.3 Extensor Digitorum Superficialis

In relation to PV a significant distance by group interaction emerged [$F(2,34)=4.60$, $p<0.05$, $\eta^2=0.21$]. Subsequent one-way ANOVAs (limb collapsed) for each distance showed that for the near [$F(2,42)=20.01$, $p<0.001$, $\eta^2=0.50$] and far object [$F(2,42)=25.15$, $p<0.001$, $\eta^2=0.56$] the YA (near=75.77ms, far=9.75ms) produced peak extensor digitorum superficialis (EDS) activity closer to PV than participants with an icSCI (Near=534.83ms, Far=624.65ms). Additionally, in both conditions the OA (Near=246.12ms, Far=225.28ms) reached peak EDS activity closer to PV than participants with an icSCI. For either distance, there was no significant difference between YA and OA ($p>0.05$). Paired t-tests revealed that for the YA [$t(15)=2.54$, $p<0.05$] time of peak EDS activity and time of PV were more tightly coupled when moving to the far object (M=9.75ms) than the near object (M=75.77ms). For OA [$t(12)=0.37$, $p>0.05$) and participants with an icSCI [$t(13)=-0.83$, $p>0.05$] there was no significant difference.

For the start of FAP there was a significant main effect of group [$F(2,34)=8.73$, $p<0.01$, $\eta^2=0.34$] as participants with an icSCI (M=-95ms) produced peak EDS activity closer to the start of FAP than YA (M=-330ms). There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). The main effects of limb and distance did not reach significance for either PV (limb [$F(1,34)=0.54$, $p>0.05$, $\eta^2=0.02$], distance [$F(1,34)=1.71$, $p>0.05$, $\eta^2=0.05$]) or the start of FAP (limb [$F(1,34)=3.39$, $p>0.05$, $\eta^2=0.09$], distance [$F(1,34)=0.41$, $p>0.05$, $\eta^2=0.01$].

6.4.4 Triceps Brachii

YA (M=25ms) and OA (M=177ms) produced peak triceps brachii activity closer to the time of PV when compared to participants with an icSCI (M=388ms) [$F(2,34)=17.14$, $p<0.001$, $\eta^2=0.50$] but there was no significant difference between YA and OA ($p>0.05$). However, there was no significant main effect of group in relation to the start of FAP [$F(2,34)=0.70$, $p>0.05$, $\eta^2=0.04$] as all groups showed a similar time difference (icSCI=-281ms, YA=-329ms, OA=-263ms). In relation to PV and start of FAP there was no significant main effect of limb (PV [$F(1,34)=0.002$, p>0.05, η^2=0.001], FAP [F(1,34)=1.63, p>0.05, η^2=0.05] or distance (PV [F(1,34)=0.17, p>0.05, η^2=0.005], FAP [F(1,34)=0.49, p>0.05, η^2=0.01].

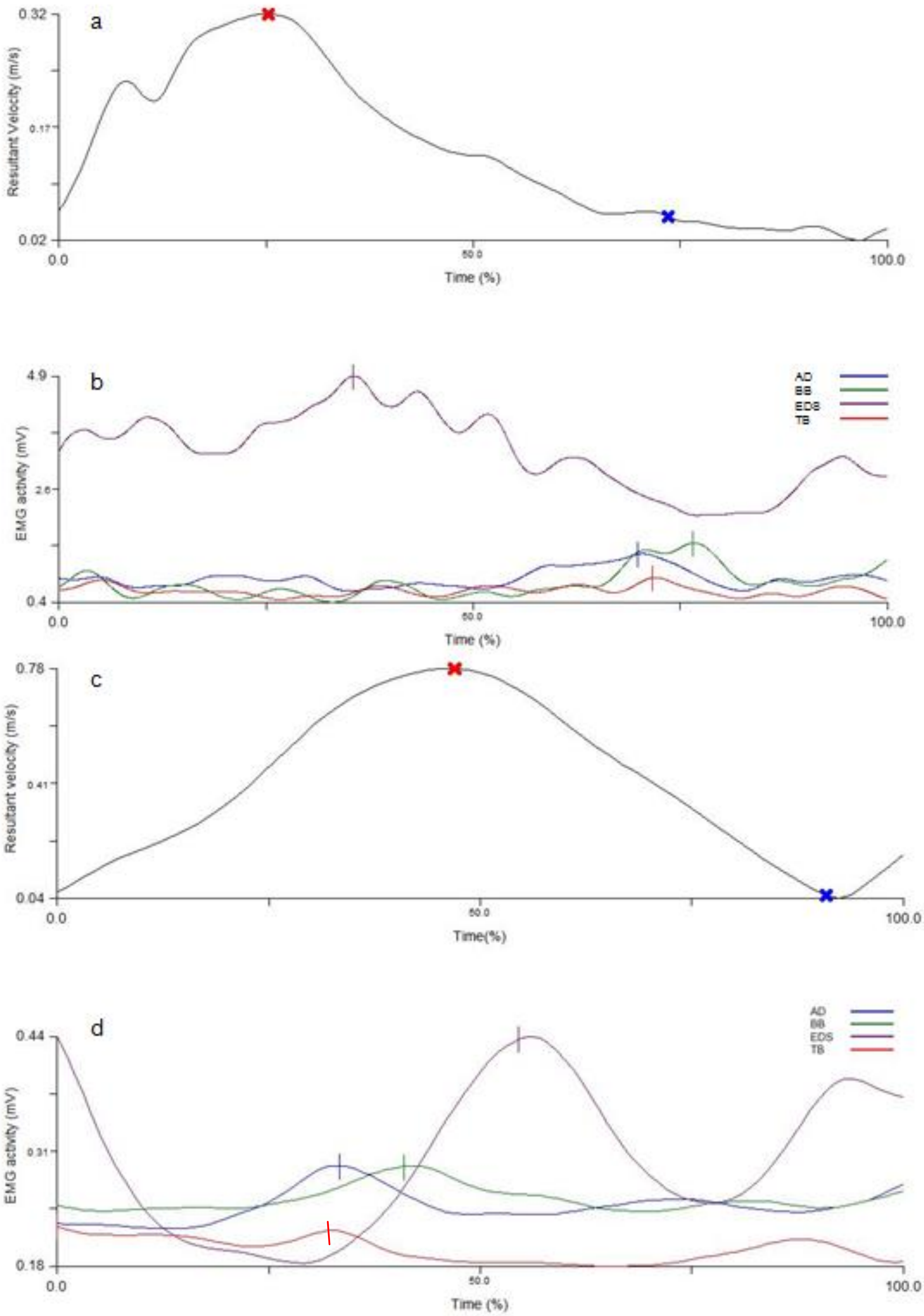

Figure 6.5: An example of a kinematic (a and c) and EMG profile (b and d) for a participant with an icSCI (a and b) and a young adult (c and d), in a unimanual

condition (graphed between the start and the end of the movement) when the preferred/less impaired limb was reaching to the near object. The cross markers on a and c show the average timing of kinematic events; peak velocity (red) and start of the final adjustment phase (blue). The tick markers on b and d show average timing of peak muscle activity for the; anterior deltoid (AD, blue), biceps brachii (BB, green), extensor digitorum superficialis (EDS, purple) and triceps brachii (TB, red).

6.4.5 Agonist-Antagonist muscle activity patterns

There was a significant main effect of group [$F(2,34)=6.99$, $p<0.01$, $\eta^2=0.29$] as the time of peak triceps brachii activity and lowest biceps brachii activity was less coupled for individuals with an icSCI (M=222ms) when compared to the YA (M=-12ms, $p<0.01$), as shown in figure 6.6. There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). No significant main effect of limb [$F(1,34)=0.04$, $p>0.05$, $\eta^2=0.001$] or distance [$F(1,34)=0.66$, $p>0.05$, $\eta^2=0.02$] or significant interactions emerged.

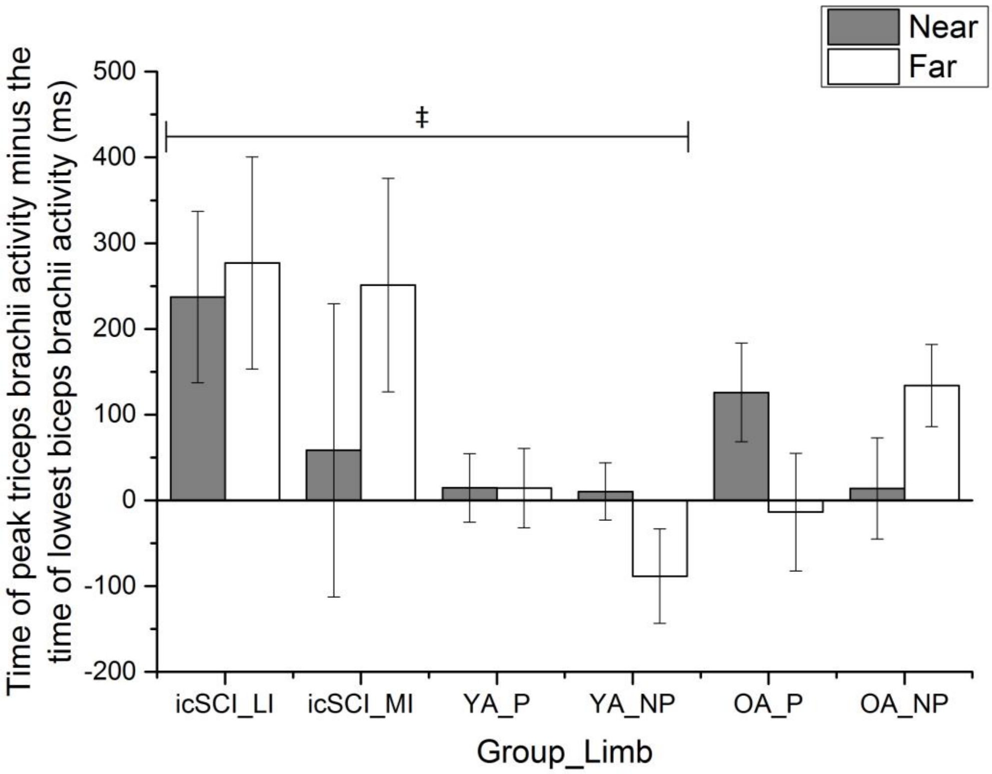

Figure 6.6: Group and limb means (±standard error) for the time difference between the timing of peak triceps brachii activity and lowest biceps brachii activity in near (grey) and far (white) conditions. (‡ represents a significant difference between

groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.4.6 Summary of results from experiment one

Participants with an icSCI produced movements of a longer duration than both YA and OA (for both limbs, figure 6.1a) with a prolonged propDT (figure 6.1c) and propFAP (figure 6.1d), and movement time was longer for the MI limb than the LI limb. Movements were also slower (lower peak velocity) than YA at both distances and slower than OA when reaching for the far object (figure 6.1b). The movements produced by participants with an icSCI were also less smooth (in both the approach (figure 6.2a) and final adjustment phases (figure 6.2b) than YA and OA, in agreement with their increased proportion of movement time spent in the deceleration and final adjustment phase. Additionally, more adjustments were made by the MI limb for participants with an icSCI than the LI limb in both these phases.

For all muscles (anterior deltoid, biceps brachii, extensor digitorum superficialis and triceps brachii) tested YA and OA produced peak muscle activity closer to the time of PV compared to participants with an icSCI. For the anterior deltoid and extensor digitorum superficialis the participants with an icSCI produced peak muscle activity closer to the start of FAP than YA, but for the biceps brachii and triceps brachii main effect of group did not reach significance although the same pattern was shown. This may have occurred due to muscle paralysis of the triceps brachii and biceps brachii following icSCI, which resulted in a decrease in co-activation between the agonist-antagonist muscle activity patterns when compared to YA (figure 6.6). For the biceps brachii there was a significant main effect of limb as peak muscle activity was closer to FAP for the P/LI limb and closer to PV for the NP/MI limb.

Distance did not influence movement time, however, peak velocity was greater when reaching for the far object, which suggests that all participants moved faster in order to cover the farther distance in the far object condition. PropDT and propFAP were greater when moving to the near compared to far object, and a distance by group interaction for the number of adjustments in the final adjustment phase showed that participants with an icSCI and OA made more adjustments when moving to the near object. Resultant path length was longer for participants with an icSCI compared to OA, and as expected longer when reaching to the far compared to near object. Finally, participants with an icSCI produced a greater maximum wrist height than YA.

In terms of the grasp phase, a distance by group interaction and subsequent analysis showed that participants with an icSCI produced a larger MGA than YA for the near object, but no group differences emerged for the far object. Additionally, participants with an icSCI produced a larger MGA when reaching for the near object compared to far object, whereas, OA produced a larger MGA when reaching for the far object. Participants with an icSCI also produced MGA earlier in the movement than YA, and all participants produced MGA earlier when reaching to the near object compared to far object. For the extensor digitorum superficialis, a distance by group interaction emerged and subsequent analysis showed that YA produced peak muscle activity closer to PV when reaching for the far object compared to near object, which coincides with the prolonged propFAP in the near object condition. Consistent with the early hand opening, transport and grasp coupling was weaker for participants with an icSCI compared to YA and OA and for all participant groups was less coupled when reaching to the far compared to near object.

Table 6.0: Group and limb means for the timing of peak muscle activity in relation to the timing of kinematic events for each unimanual distance condition (AD=Anterior Deltoid, B=Biceps Brachii, E=Extensor Digitorum Superficialis, T=Triceps Brachii, ST=start of the movement, PV=peak velocity, FAP=start of the final adjustment phase and END=end of the movement). The nearest kinematic event is in **bold**.

P/LI limb Near																
	P_AD-ST (ms)	P_AD-PV (ms)	P_AD-FAP (ms)	P_AD-END (ms)	P_B-ST (ms)	P_B-PV (ms)	P_B-FAP (ms)	P_B-END (ms)	P_E-ST (ms)	P_E-PV (ms)	P_E-FAP (ms)	P_E-END (ms)	P_T-ST (ms)	P_T-PV (ms)	P_T-FAP (ms)	P_T-END (ms)
icSCI	901.8	517.7	**-45.3**	-415.9	891.7	507.6	**-55.5**	-426.2	883.1	499.00	**-64.0**	-434.7	693.1	309.0	**-254.0**	-624.7
YA	270.9	**-10.0**	-372.6	-466.8	289.6	**8.7**	-353.9	-448.2	345.3	**64.37**	-298.2	-392.5	357.3	**76.4**	-286.2	-380.5
OA	611.2	321.1	**-120.4**	-245.2	573.9	283.8	**-157.6**	-282.5	598.8	308.72	**-132.7**	-257.6	510.7	**220.5**	-220.9	-345.8
NP/MI limb Near																
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	891.4	480.8	**-227.20**	-826.9	828.4	417.8	**-290.2**	-889.9	1017.9	607.3	**-100.7**	-700.4	748.9	**338.3**	-369.7	-969.4
YA	351.5	**74.4**	-280.9	-355.1	340.0	**63.0**	-292.3	-366.6	364.2	**87.2**	-268.1	-342.4	354.2	**77.2**	-278.1	-352.3
OA	565.1	231.9	**-180.7**	-292.3	557.5	224.3	**-188.3**	-299.9	516.7	**183.5**	-229.1	-340.7	436.6	**103.4**	-309.2	-420.8
P/LI limb Far																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	952.5	519.5	**-130.9**	-401.9	797.5	364.5	**-286.0**	-556.9	834.8	401.8	**-248.7**	-519.6	822.0	389.0	**-261.4**	-532.4
YA	285.8	**-20.6**	-390.33	-449.8	284.8	**-21.6**	-391.3	-450.8	294.5	**-11.8**	-381.6	-441.1	299.5	**-6.9**	-376.7	-436.1
OA	590.3	285.8	**-187.7**	-282.0	527.0	**222.5**	-251.0	-345.4	566.4	261.9	**-211.7**	-306.0	461.3	**156.8**	-316.7	-411.1
NP/MI limb Far																
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1162.3	832.08	**61.8**	-512.3	836.9	506.7	**-263.6**	-837.7	1199.6	869.4	**99.1**	-475.0	959.3	629.1	**-141.2**	-715.4
YA	302.2	**1.6**	-350.1	-407.7	238.2	**-62.3**	-414.0	-471.6	311.9	**11.4**	-340.3	-398.0	273.9	**-26.6**	-378.3	-436.0
OA	570.8	241.3	**-205.9**	-291.0	486.7	**157.2**	-290.0	-375.1	485.0	**155.5**	-291.7	-376.8	504.7	**175.2**	-272.0	-357.1

6.5 Results for Experiment two – Kinematic data

6.5.1 Movement time

Figure 6.7a shows that there was a significant main effect of group [$F(2,40)=23.06$, $p<0.001$, $\eta^2=0.54$] as participants with an icSCI (M=1591ms) produced movements of a longer duration than YA (M=705ms) and OA (M=890ms). There was also a significant main effect of size [$F(1,40)=13.34$, $p<0.01$, $\eta^2=0.25$] as movement time to the large object (M=1126ms) was longer than to the small object (M=998ms). The main effect of limb did not reach significance [$F(1,40)=3.92$, $p>0.05$, $\eta^2=0.09$].

A significant size by group interaction (limb collapsed) emerged [$F(2,40)=9.66$, $p<0.001$, $\eta^2=0.33$] and subsequent one-way ANOVAs revealed that for the small [$F(2,49)=26.69$, $p<0.001$, $\eta^2=0.53$] and large object [$F(2,47)=19.96$, $p<0.001$, $\eta^2=0.47$] there was a significant difference between groups as participants with icSCI (Small=1430ms, Large=1685ms) produced movements of a longer duration than YA (Small=717ms, Large=693ms) and OA (Small=863ms, Large=917ms). Paired t-tests revealed that for participants with an icSCI [$t(15)=-2.27$, $p<0.05$] movement to the large object (M=1685ms) resulted in a longer movement time than when reaching and grasping the small object (M=1387ms). There was no significant difference between conditions for YA [$t(15)=0.90$, $p>0.05$] or OA [$t(15)=-1.39$, $p>0.05$].

6.5.2 Peak velocity

There was a significant main effect of group [$F(2,40)=10.11$, $p<0.001$, $\eta^2=0.34$], as seen in figure 6.7b, as participants with an icSCI (M=500mm/s) reached significantly lower PV than YA (M=724mm/s). No significant difference emerged between participants with an icSCI and OA or YA and OA ($p>0.05$). There was no significant main effect of size [$F(1,40)=1.43$, $p>0.05$, $\eta^2=0.04$] or limb [$F(1,40)=1.20$, $p>0.05$, $\eta^2=0.03$] but a significant size by limb interaction emerged [$F(1,40)=6.56$, $p<0.05$, $\eta^2=0.14$].

To investigate the size by limb interaction paired t-tests (group collapsed) for the small [$t(46)=-1.42$, $p>0.05$] and large [$t(44)=0.59$, $p>0.05$] object revealed that there was no significant difference in PV between P/LI and NP/MI limbs. Further paired t-tests (for each limb to identify any differences between object size) revealed that for the P/LI limb PV was significantly greater when reaching for the large object (M=623mm/s) compared to the small (M=598mm/s) object [$t(47)=-2.25$, $p<0.05$]. For the NP/MI limb there was no significant difference in PV between object sizes [$t(42)=0.26$, $p>0.05$].

6.5.3 Proportion of movement time spent decelerating

Figure 6.7c shows that participants with an icSCI (M=71.79%) spent a longer proportion of movement time decelerating compared to YA (M=60.08%) [$F(2,40)=10.91$, $p<0.001$, $\eta^2=0.35$]. However, no significant difference emerged between participants with an icSCI and OA (M=65.87%), but OA spent a longer proportion of the movement decelerating that YA ($p<0.05$). There was no significant main effect of size [$F(1,40)=2.33$, $p>0.05$, $\eta^2=0.06$] or limb [$F(1,40)=0.57$, $p>0.05$, $\eta^2=0.01$] and no significant interactions emerged.

6.5.4 Proportion of movement time spent in the final adjustment phase

As evident in figure 6.7d there was a significant main effect of group [$F(2,40)=9.18$, $p<0.01$, $\eta^2=0.32$] as participants with an icSCI (M=33.17%) spent a greater proportion of the movement in the final adjustment phase (propFAP) than YA (M=10.69%) and OA (M=18.20%). No significant difference between YA and OA emerged ($p>0.05$). There was a significant main effect of size [$F(1,40)=21.19$, $p<0.001$, $\eta^2=0.35$] as a longer propFAP emerged when reaching to the large object (M=23.20%) compared to small object (M=18.18%). There was no significant main effect of limb [$F(1,40)=0.86$, $p>0.05$, $\eta^2=0.02$] but a significant size by group interaction emerged [$F(2,40)=9.10$, $p<0.01$, $\eta^2=0.31$].

To explore the size by group interaction one-way ANOVAs to determine group differences for each object size (limb collapsed) revealed that for the small [$F(2,49)=8.04$, $p<0.01$, $\eta^2=0.26$] and large [$F(2,47)=9.93$, $p<0.001$, $\eta^2=0.31$] object there was a significant difference between groups as participants with an icSCI (Small=28.15%, Large=34.57%) spent a longer proportion of the movement in the final adjustment phase compared to YA (Small=10.41%, Large=10.97%) and OA (Small=16.89%, Large=19.50%). Paired t-tests revealed that for participants with an icSCI [$t(15)=-3.31$, $p<0.01$] propFAP was significantly longer when reaching for the large object (icSCI=34.57%) compared to the small object (icSCI=25.23%). However, there was no significant difference for YA [$t(15)=-0.43$, $p>0.05$] or OA [$t(15)=-1.81$, $p>0.05$].

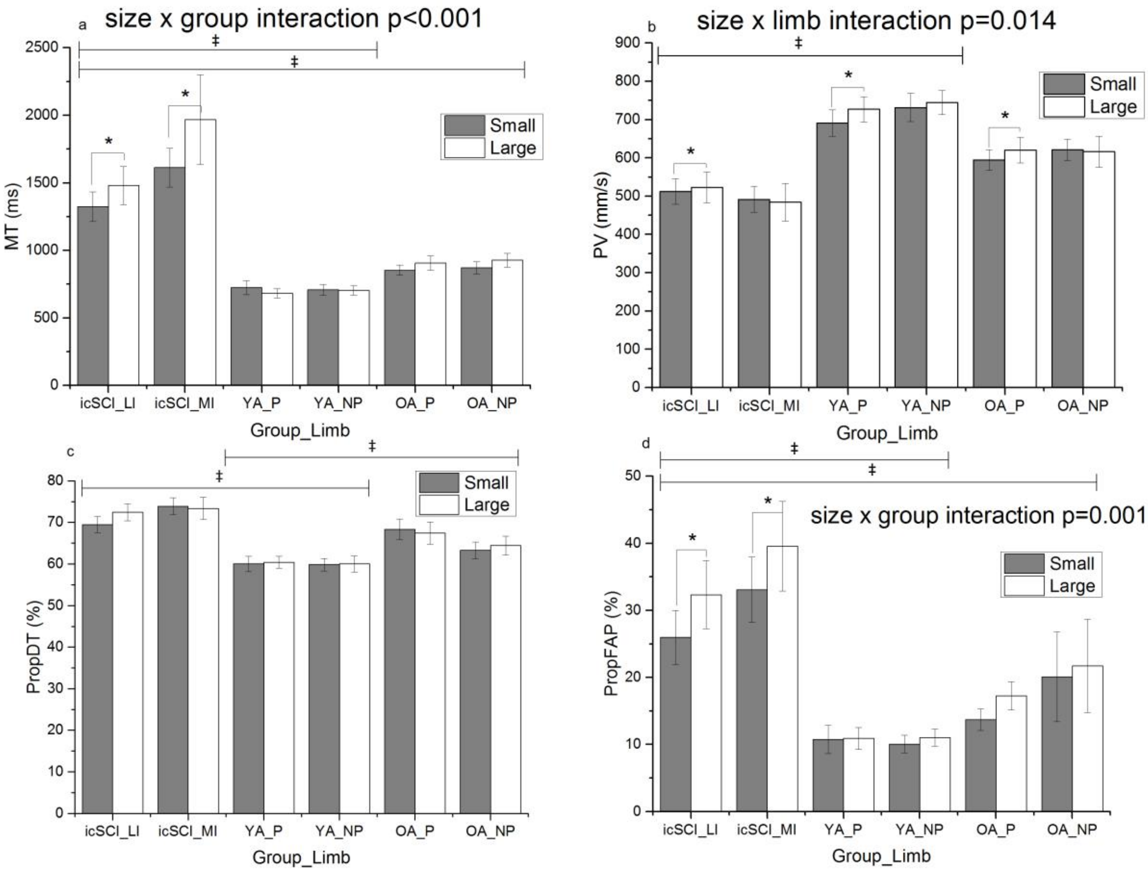

Figure 6.7: Group and limb means (±standard error) for movement time (MT) (a), peak velocity (PV) (b), proportion of movement time spent decelerating (propDT) (c) and proportion of movement time spent in final adjustment phase (propFAP) (d) when reaching for the small (grey) and large (white) object conditions. (* denotes significant difference between small and large objects and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical spinal cord injury less impaired limb, icSCI_MI = incomplete cervical spinal cord injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.5.5 Number of adjustments in the approach phase

As shown in figure 6.8a there was a significant main effect of group [$F(2,40)=36.77$, $p<0.001$, $\eta^2=0.65$] as participants with an icSCI (M=3.35) made more adjustments than YA (M=0.42) and OA (M=1.31). Additionally, OA produced more adjustments than YA ($p<0.05$). There was no significant main effect of size [$F(1,40)=1.51$, $p>0.05$, $\eta^2=0.04$] or limb [$F(1,40)=3.69$, $p>0.05$, $\eta^2=0.08$] and no significant interactions emerged.

6.5.6 Number of adjustments in the final adjustment phase

A significant main effect of group arose (figure 6.8b) [$F(2,40)=11.24$, $p<0.001$, $\eta^2=0.36$] as participants with an icSCI (M=6.32) produced more adjustments than YA (M=0.91) and OA (M=1.71). No significant difference between YA and OA emerged ($p>0.05$). There was a significant main effect of size [$F(1,40)=11.90$, $p<0.01$, $\eta^2=0.23$] as more adjustments were made when reaching and grasping the large object (M=3.61) compared to the small object (M=2.35, $p<0.01$). There was no significant main effect of limb [$F(1,40)=1.51$, $p>0.05$, $\eta^2=0.04$] but a significant size by group interaction emerged [$F(2,40)=8.50$, $p<0.01$, $\eta^2=0.30$].

To investigate the size by group interaction one-way ANOVAs (limb collapsed), to determine group differences for each object size, revealed for the small [$F(2,49)=12.63$, $p<0.001$, $\eta^2=0.35$] and large object [$F(2,48)=10.76$, $p<0.001$, $\eta^2=0.47$] there was a significant difference between groups as participants with an icSCI (Small=5.26, Large=7.29) produced more adjustments that YA (Small=0.98, Large=0.85) and OA (Small=1.51, Large=1.91). No significant difference between YA and OA emerged ($p>0.05$). Paired t-tests (for each group to determine differences between object size) revealed that participants with an icSCI [$t(16)=-2.21$, $p<0.05$] made more adjustments when reaching to the large object (M=7.29) compared to the small object (M=4.63). There was no significant difference between object sizes for YA [$t(15)=1.24$, $p>0.05$] or OA [$t(15)=-1.77$, $p>0.05$].

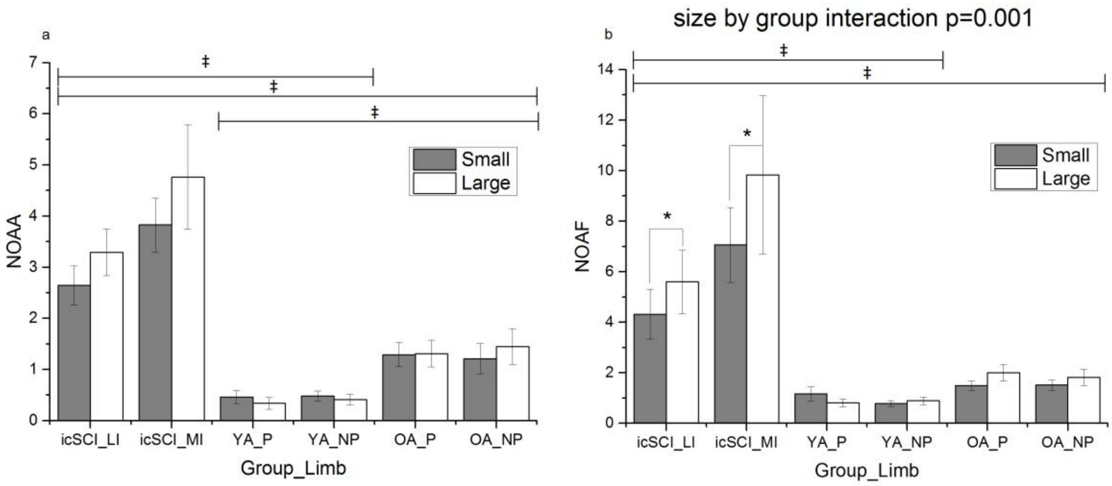

Figure 6.8: Group and limb means (±standard error) for number of adjustments in the approach phase (NOAA) (a) and number of adjustments in the final adjustment phase (NOAF) (b) when reaching for the small (grey) and large (white) object. (‡ represents a significant difference between groups, * denotes a significant difference between small and large objects), (icSCI_LI = incomplete cervical spinal cord injury less impaired limb,

icSCI_MI = incomplete cervical spinal cord injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.5.7 Maximum grasp aperture

There was no significant main effect of group [$F(2,40)=2.54$, $p>0.05$, $\eta^2=0.11$] but there was a significant main effect of size [$F(1,40)=1037.83$, $p<0.001$, $\eta^2=0.96$] as MGA was larger when reaching to the large (M=12cm) object compared to small object (M=9.3cm) shown in figure 6.9a. There was no significant main effect of limb [$F(1,40)=1.20$, $p>0.05$, $\eta^2=0.03$] but a significant size by group interaction emerged [$F(2,40)=4.18$, $p<0.05$, $\eta^2=0.17$].

To explore the size by group interaction paired t-tests (limb collapsed) were performed to determine the difference between object sizes for each group, and revealed that for all groups (icSCI [$t(15)=-11.73$, $p<0.001$], YA [$t(15)=-26.17$, $p<0.001$] and OA [$t(15)=-18.35$, $p<0.001$]) MGA was scaled to object size as a larger MGA was formed when reaching for the large object (icSCI=9.84 vs 11.99cm, YA=9.08 vs 12.02cm, OA=9.19 vs 11.74cm). One-way ANOVAs (to determine group differences for each object size) revealed that for the small object there was a significant difference between groups [$F(2,49)=3.99$, $p<0.05$, $\eta^2=0.10$] as participants with an icSCI (M=9.69cm) produced larger MGA's than YA (M=9.08cm, $p<0.05$). No significant difference emerged between YA and OA ($p>0.05$). For the large object there was no significant difference between groups [$F(2,47)=0.73$, $p>0.05$, $\eta^2=0.001$].

6.5.8 Time of maximum grasp aperture as a percentage of movement time

Participants with an icSCI (M=51.65%) reached MGA earlier in the movement than YA (M=68.11%) and OA (M=63.16%) (figure 6.9b) [$F(2,40)=10.06$, $p<0.001$, $\eta^2=0.34$]. There was no significant difference between YA and OA ($p>0.05$). No significant main effect of size [$F(1,40)=0.88$, $p>0.05$, $\eta^2=0.02$], limb [$F(1,40)=0.01$, $p>0.05$, $\eta^2=0.002$] and no significant interactions between variables emerged.

6.5.9 Transport and grasp coupling

As shown by figure 6.9c participants with an icSCI (M=219ms) produced less coupled transport and grasp phases than YA (M=59ms) and OA (M=95ms) [$F(2,40)=9.69$, $p<0.001$, $\eta^2=0.32$]. There was no significant difference between YA and OA ($p>0.05$). A significant main effect of size emerged [$F(1,40)=10.32$, $p<0.01$, $\eta^2=0.21$] as transport and grasp coupling was stronger when reaching to the small (M=96ms) compared to large (M=147ms) object. There was no significant main effect of limb [$F(1,40)=1.72$, $p>0.05$, $\eta^2=0.04$] and no significant interactions emerged.

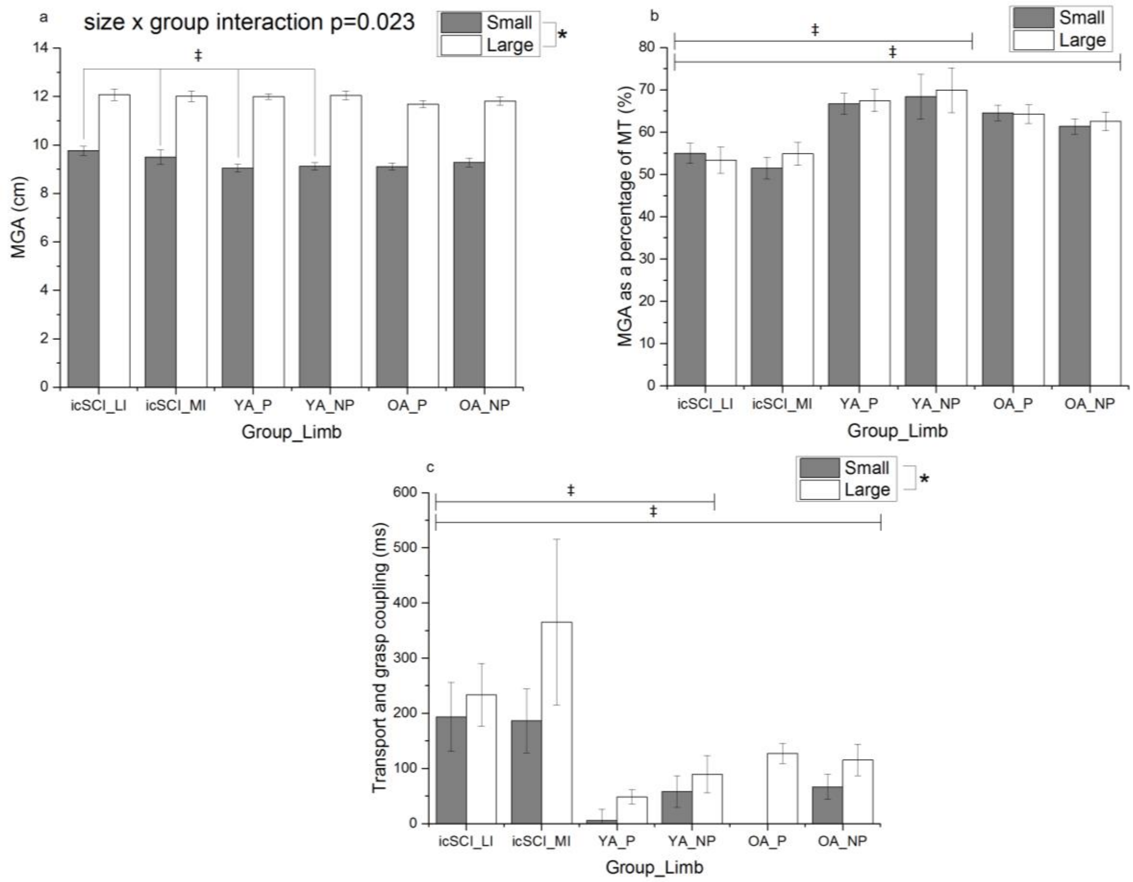

Figure 6.9: Group and limb means (±standard error) for maximum grasp aperture (MGA) (a), time of maximum grasp aperture as a percentage of movement time (MGA as a percentage of MT) (b) and transport and grasp phase coupling (c) when reaching for the small (grey) and large (white) object. (* denotes significant difference between small and large objects and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical spinal cord injury less impaired limb, icSCI_MI = incomplete cervical spinal cord injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.5.10 Path length

Participants with an icSCI (M=29.4cm) produced movements with a longer resultant path length than YA (M=24.5cm) and OA (M=23.7cm) [$F(2,40)=5.75$, $p<0.01$, $\eta^2=0.22$] as shown in figure 6.10a. There was no significant main effect of size [$F(1,40)=0.69$, p>0.05, η^2=0.02] or limb [F(1,40)=0.24, p>0.05, η^2=0.01] and no significant interactions emerged.

With regards to path length in the vertical direction (z) there was no significant main effect of group [F(2,40)=1.89, p>0.05, η^2=0.09], size [F(1,40)=1.55, p>0.05, η^2=0.04] or limb [F(1,40)=0.24, p>0.05, η^2=0.006] and no significant interactions emerged (figure 6.10b). As shown in figure 6.10c participants with an icSCI (M=20.5cm) produced a greater maximal wrist height compared to YA (M=11.5cm) [F(2,40)=6.17, p<0.01, η^2=0.24], with no significant difference emerging between participants with an icSCI and OA or YA and OA (p>0.05). There was no significant main effect of size [F(1,40)=1.38, p>0.05, η^2=0.03] or limb [F(1,40)=1.91, p>0.05, η^2=0.05] on maximum wrist height.

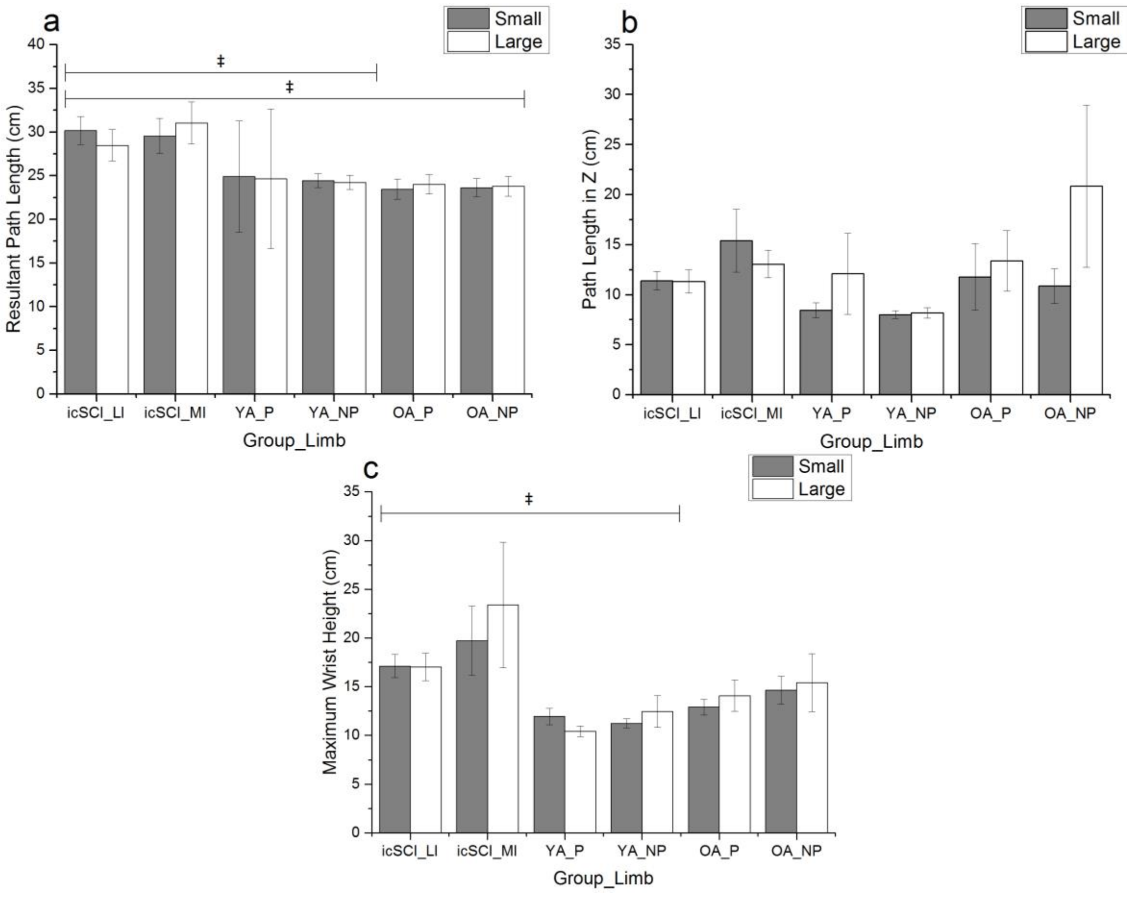

Figure 6.10: Group and limb means (±standard error) for resultant path length (a), path length in the vertical direction (z) (b) and maximum wrist height (c) when reaching for the small (grey) and large (white) object. (‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical spinal cord injury less impaired limb, icSCI_MI = incomplete cervical spinal cord injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb,

OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

6.6 Electromyography analysis

For the timing of peak muscle activity in relation to kinematic events it is clear from table 6.1 that for all participants this occurs between Peak Velocity and the start of the final adjustment phase. Therefore this was the focus of the subsequent statistical analyses.

6.6.1 Anterior Deltoid

In relation to PV there was a significant main effect of group [$F(2,34)=35.92$, $p<0.001$, $\eta^2=0.68$] as YA (M=31ms) produced peak anterior deltoid activity closer to the time of PV than participants with an icSCI (M=690ms). A significant difference between OA (M=267ms) and participants with an icSCI also occurred ($p<0.05$), but no significant difference between YA and OA emerged ($p>0.05$). In relation to the start of FAP there was also a significant main effect of group [$F(2,34)=12.70$, $p<0.001$, $\eta^2=0.43$] as participants with an icSCI (M=44ms) produced peak anterior deltoid activity closer to (and after) the start of FAP than YA (M=-318ms) and OA (M=-169ms). There was no significant difference between YA and OA ($p>0.05$). There was no significant main effect of limb (PV [$F(1,34)=0.01$, $p>0.05$, $\eta^2=0.001$], FAP [$F(1,34)=1.24$, $p>0.05$, $\eta^2=0.04$]) but there was a significant main effect of size (PV [$F(1,34)=9.81$, $p<0.01$, $\eta^2=0.22$], FAP [$F(1,34)=7.40$, $p<0.05$, $\eta^2=0.18$]) as peak anterior deltoid activity was closer to PV when reaching for the small object (small=-277ms, large=382ms) but closer to the start of FAP when reaching for the large object (small=-187ms, large=-108ms).

In relation to PV [$F(2,34)=7.36$, $p<0.01$, $\eta^2=0.30$] and start of FAP [$F(2,34)=6.54$, $p<0.01$, $\eta^2=0.28$] a size by group interaction emerged and subsequent one-way ANOVAs (limb collapsed) showed that for the small [$F(2,42)=24.73$, $p<0.001$, $\eta^2=0.52$] and large objects [$F(2,41)=24.11$, $p<0.001$, $\eta^2=0.55$] YA (small=32.18ms, large=48.87ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI (small=489.78ms, large=714.45ms). In addition, OA (small=276.52ms, large=257.99ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI. With respect to the start of FAP, one-way ANOVAs (to determine group differences for both object sizes) showed that for the small [$F(2,42)=4.96$, $p<0.05$, $\eta^2=0.20$] and large object [$F(2,42)=7.89$, $p<0.01$, $\eta^2=0.28$] participants with an icSCI (small=-136.25ms, large=52.62ms) produced peak anterior deltoid activity closer to the start of FAP than YA (small=-326.73ms, large=-277.99ms). There was no significant difference between YA and OA or participants with an icSCI and OA for either object size ($p>0.05$).

Paired t-tests (to determine the difference between object sizes for each group) showed that in relation to PV and start of FAP there was no significant difference between object sizes for YA (PV [$t(14)=-1.27$, $p>0.05$], FAP [$t(15)=-1.86$, $p>0.05$]) and OA (PV [$t(12)=0.49$, $p>0.05$], FAP [$t(12)=1.14$, $p>0.05$]). However, for participants with an icSCI peak anterior deltoid activity occurred closer to PV [$t(13)=-2.61$, $p<0.05$] when reaching for the small object (small=489.78ms, large=714.45ms) and closer to the start of FAP [$t(13)=-2.88$, $p<0.05$] when reaching for the large object (small=-136.25ms, large=52.62ms).

6.6.2 Biceps Brachii

A significant main effect of group emerged [$F(2,34)=26.63$, $p<0.001$, $\eta^2=0.61$] as YA (M=27ms) produced peak biceps brachii activity closer to the time of PV when compared to participants with an icSCI (M=622ms) and OA (M=268ms). There was also a significant difference between participants with an icSCI and OA ($p<0.05$). With regards to the start of FAP [$F(2,34)=8.72$, $p<0.01$, $\eta^2=0.34$] participants with an icSCI (M=-24ms) produced peak biceps brachii activity that was closer to the start of FAP than YA (M=-322ms). There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). No significant main effect of size (PV [$F(1,34)=3.74$, $p>0.05$, $\eta^2=0.10$], FAP [$F(1,34)=2.29$, $p>0.05$, $\eta^2=0.06$]), limb (PV [$F(1,34)=0.72$, $p>0.05$, $\eta^2=0.02$], FAP [$F(1,34)=2.34$, $p>0.05$, $\eta^2=0.07$]) or significant interactions emerged.

6.6.3 Extensor Digitorum Superficialis

There was a significant main effect of group in relation to PV [$F(2,34)=20.96$, $p<0.001$, $\eta^2=0.55$] and start of FAP [$F(2,34)=4.45$, $p<0.05$, $\eta^2=0.21$] as YA (M=52ms) produced peak EDS activity closer to the time of PV than participants with an icSCI (M=584ms) and OA (M=270ms). OA also produced peak extensor digitorum superficialis activity closer to the time of PV than participants with an icSCI ($p<0.05$). Participants with an icSCI produced extensor digitorum superficialis activity closer to the start of FAP than YA (M=-298ms). There was no significant difference between participants with an icSCI and OA or YA and OA in terms of time difference to the start of FAP ($p>0.05$). No significant main effects of size (PV [$F(1,34)=0.37$, $p>0.05$, $\eta^2=0.01$] , FAP [$F(1,34)=0.002$, $p>0.05$, $\eta^2=0.001$]), limb (PV [$F(1,34)=1.19$, $p>0.05$, $\eta^2=0.034$], FAP [$F(1,34)=3.91$, $p>0.05$, $\eta^2=0.10$]) or significant interactions emerged.

6.6.4 Triceps Brachii

A significant main effect of group emerged [$F(2,34)=22.11$, $p<0.001$, $\eta^2=0.57$] as YA (M=48ms) produced peak triceps brachii activity closer to time of PV than participants with icSCI (M=432ms). OA (M=168ms) also produced peak triceps brachii activity closer to time of PV than participants with an icSCI. There was no significant difference between YA and OA ($p<0.05$). The main effect of group did not reach significance for the start of FAP [$F(2,34)=1.20$, $p>0.05$, $\eta^2=0.07$]. There was no significant main effect of size (PV [$F(1,34)=1.86$, $p>0.05$, $\eta^2=0.05$], FAP [$F(1,34)=0.55$, $p>0.05$, $\eta^2=0.02$]) or limb (PV [$F(1,34)=0.005$, $p>0.05$, $\eta^2=0.001$], FAP [$F(1,34)=0.87$, $p>0.05$, $\eta^2=0.03$]) for PV or start of FAP and no significant interactions emerged.

6.6.5 Agonist-Antagonist muscle activity patterns

A significant main effect of group emerged [$F(2,34)=3.54$, $p<0.05$, $\eta^2=0.172$] as the timing of peak triceps brachii (agonist) activity and lowest biceps brachii (antagonist) was less coupled for individuals with an icSCI (M=178ms) than YA (M=-10ms) as seen in figure 6.11. There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). The main effects of limb [$F(1,34)=1.55$, $p>0.05$, $\eta^2=0.04$] and size [$F(1,34)=0.44$, $p>0.05$, $\eta^2=0.01$] did not reach significance and no significant interactions emerged.

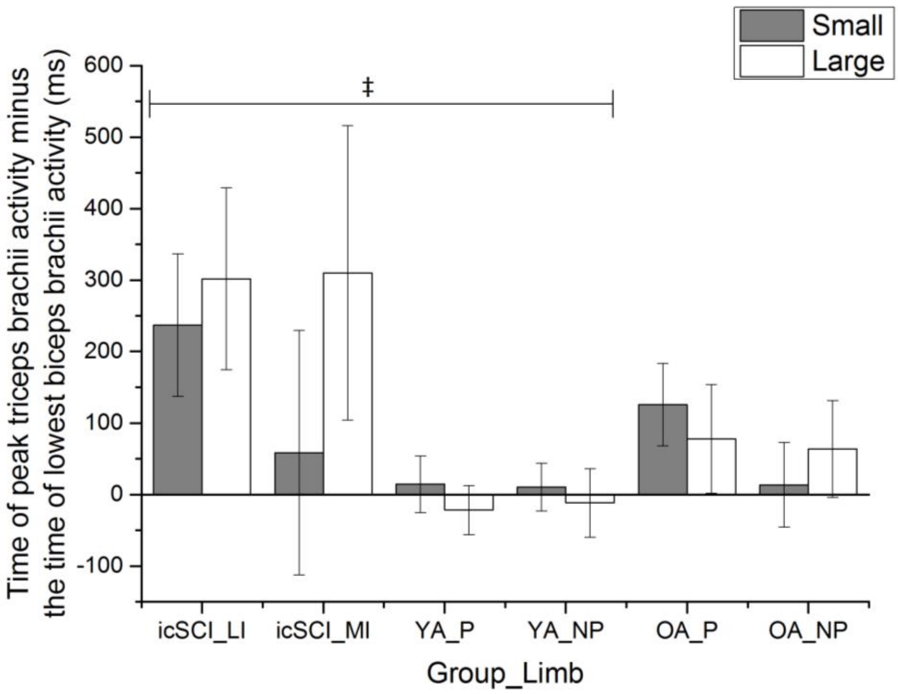

Figure 6.11: Group and limb means (±standard error) for the time difference between the timing of peak triceps brachii activity and lowest biceps brachii activity when reaching for the small (grey) and large (white) object. (‡ represents a significant

difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb.

6.6.6 Summary of results from experiment two

Movement time (figure 6.7a) was longer for participants with an icSCI compared to YA and OA (for both object sizes) and peak velocity (figure 6.7b) was reduced when compared to YA. Participants with an icSCI spent a longer proportion of the movement time decelerating (figure 6.7c) compared to YA and a longer proportion of the movement time in the final adjustment phase (figure 6.7d) than both YA and OA. Additionally, OA spent a longer proportion of the movement decelerating compared to YA, but this group difference did not continue into the final adjustment phase. The results for the number of adjustments (in both the approach (figure 6.8a) and final adjustment phases (figure 6.8b)) mirrored these findings, as more adjustments were made by participants with an icSCI compared to YA and OA in both phases, and OA more than YA in the approach phase.

Size by group interactions for movement time, propFAP and number of adjustments in the final adjustment phase showed that for participants with an icSCI, movements were longer in duration with a greater propFAP when moving to the large object, with no difference between object sizes for YA or OA. For all participants group, peak velocity for the P/LI limb was greater when reaching to the large compared to small object but this difference between object sizes did not emerge for the NP/MI limb.

With regards to the grasp phase, all participants scaled their MGA to object size with a larger MGA produced when reaching and grasping the large object (figure 6.9a). A group difference in MGA emerged for the small object as participants with an icSCI produced a larger MGA than YA. Participants with an icSCI produced MGA earlier than both YA and OA (figure 6.9b) and therefore produced transport and grasp phases that were less coupled than YA and OA (figure 6.9c). The transport and grasp phases were also less coupled when reaching and grasping the large compared to small object for all participants. Finally, resultant path length (figure 6.10a) was significantly longer for participants with an icSCI compared to YA and OA and maximum wrist height was significantly greater than YA (figure 6.10b).

For all muscles tested (anterior deltoid, biceps brachii, extensor digitorum superficialis and triceps brachii), YA and OA produced peak muscle activity closer to PV than participants with an icSCI. For the biceps brachii and extensor superficialis digitorum YA also produced peak muscle activity closer to PV than OA. Participants with an icSCI produced peak muscle activity closer to the start of FAP than YA for all muscles, however, this difference did not reach significance for the triceps brachii. The timing between the peak agonist (triceps brachii) and lowest antagonist (biceps brachii) muscle activity was also weaker for participants with an icSCI compared to YA (figure 6.11). Object size influenced the timing of the anterior deltoid, but only for participants with an icSCI, as peak muscle activity was closer to PV for the small object and start of FAP for the large object.

Table 6.1: Group and limb means for the timing of peak muscle activity in relation to the timing of kinematic events for each unimanual size condition (AD=Anterior Deltoid, B=Biceps Brachii, E=Extensor Digitorum Superficialis, T=Triceps Brachii, ST=start of the movement, PV=peak velocity, FAP=start of the final adjustment phase and END=end of the movement). The nearest kinematic event is in **bold**.

P/LI limb Small																
	P_AD-ST (ms)	P_AD-PV (ms)	P_AD-FAP (ms)	P_AD-END (ms)	P_B-ST (ms)	P_B-PV (ms)	P_B-FAP (ms)	P_B-END (ms)	P_E-ST (ms)	P_E-PV (ms)	P_E-FAP (ms)	P_E-END (ms)	P_T-ST (ms)	P_T-PV (ms)	P_T-FAP (ms)	P_T-END (ms)
icSCI	901.8	517.7	**-45.30**	-415.9	891.7	507.6	**-55.5**	-426.2	883.1	499.0	**-64.0**	-434.7	693.1	309.0	**-254.0**	-624.7
YA	270.9	**-10.0**	-372.6	-466.8	289.6	**8.7**	-353.9	-448.2	345.3	**64.4**	-298.2	-392.5	357.3	**76.4**	-286.2	-380.5
OA	611.2	321.1	**-120.4**	-245.2	573.9	283.8	**-157.6**	-282.5	598.8	308.7	**-132.7**	-257.6	510.6	**220.5**	-220.9	-345.8
NP/MI limb Small																
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	891.4	480.8	**-227.2**	-826.9	828.4	417.8	**-290.2**	-889.9	1018.0	607.3	**-100.7**	-700.4	748.9	**338.3**	-369.7	-969.4
YA	351.5	**74.4**	-280.9	-355.1	340.0	**63.0**	-292.3	-366.6	364.2	**87.2**	-268.1	-342.4	354.2	**77.2**	-278.1	-352.3
OA	565.1	232.0	**-180.7**	-292.3	557.5	224.3	**-188.3**	-299.9	516.7	**183.5**	-229.1	-340.7	436.6	**103.4**	-309.2	-420.8
P/LI limb Large																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	996.9	625.7	**2.4**	-596.8	1093.7	722.5	**99.3**	-499.9	1052.2	681.0	**57.7**	-541.4	889.9	518.7	**-104.6**	-703.8
YA	317.9	**50.2**	-300.5	-374.6	271.04	**3.4**	-347.4	-421.4	325.7	**58.1**	-292.7	-366.7	308.2	**40.6**	-310.2	-384.3
OA	582.02	260.6	**-180.2**	-370.4	573.6	252.1	**-188.7**	-378.8	597.8	276.3	**-164.5**	-354.6	478.7	**157.2**	-283.6	-473.7
NP/MI limb Large																
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1404.8	891.6	**158.0**	-812.9	1045.3	532.2	**-201.5**	-1172.4	1167.0	653.8	**-79.8**	-1050.8	1163.0	649.7	**-83.9**	-1054.9
YA	325.5	**47.5**	-292.5	-374.6	324.2	**46.2**	-293.8	-375.8	281.3	**3.4**	-336.7	-418.8	312.7	**34.7**	-305.3	-387.4
OA	581.7	255.4	**-195.3**	-358.2	636.4	310.1	**-140.6**	-303.5	638.4	312.1	**-138.6**	-301.5	515.8	**189.6**	-261.1	-424.0

6.7 Discussion

This study is the first to quantify how object distance and object size influence unimanual prehension after icSCI, and how this differs to non-injured YA and OA. It is also novel in that it examines the timing of peak muscle activity in relation to kinematic events using surface EMG.

6.7.1 Transport phase

In agreement with hypothesis one and previous literature, participants with an icSCI produced movements of a longer duration than YA and OA (figures 6.1a and 6.7a), and reached a lower peak velocity than YA in both experiments and OA in experiment one. (figures 6.1b and 6.7b) (Mateo et al., 2013, Hoffmann et al., 2006, de los Reyes-Guzmán et al., 2010, Laffont et al., 2000). The emergence and subsequent analysis of a limb by group interaction (in experiment one) indicated that the movement time for the participants with an icSCI was longer for the more impaired limb than the less impaired limb.

This movement slowing (increased movement time and lower peak velocity), seen in both experiments, could have occurred due to the decreased agonist-antagonist muscle activity seen between the triceps brachii and biceps brachii (figure 6.6 and 6.11), as in non-injured individuals the triceps brachii serves to extend the elbow and the biceps brachii acts to stop further elbow extension and start the return of the limb (elbow flexion) (Koshland et al., 2005, Hughes et al., 2009). Therefore, participants with an icSCI may adopt the movement slowing strategy in order to decrease the reliance on the biceps brachii to stop the movement, as faster movements require a greater braking force in order to slow the limb down (Hughes et al., 2009). The EMG data showed that participants with an icSCI produced peak anterior deltoid, biceps brachii and extensor digitorum superficialis muscle activity closer to the start of the final adjustment phase when compared to YA (figure 6.5). The later peak muscle activity may be a novel muscle strategy to act as a braking force and prevent further extension of the limb. The novel muscle strategy seen in participants with an icSCI supports the notion of motor redundancy (Koshland et al., 2005) following icSCI, as different muscle activation patterns were seen to non-injured YA and OA (supporting hypothesis two). The development of novel muscle activity patterns also suggests that neuroplasticity of spared fibres, e.g. the CST (Oudega and Perez, 2012), has occurred to preserve reach to grasp function of the arm and hand, which is greatest in the acute stages of injury (Curt et al., 2008).

Another explanation for the motor slowing may be that participants with an icSCI slow their movements down in order to maintain accuracy during the reach-to-grasp task, as per the speed accuracy trade off (Fitts, 1954, Mateo et al., 2015). The aim to maintain accuracy is also supported by larger and earlier MGA formation in the grasp phase (see 6.7.2 below), as these strategies allow a larger margin for error correction in finger and thumb placement around the object.

Participants with an icSCI spent a longer proportion of the movement decelerating (figure 6.1c and 6.7c), and in the final adjustment phase (figure 6.1d and 6.7d) when compared to YA and OA, and also made significantly more adjustments in the approach and final adjustment phase (in both experiments). This increased reliance on the deceleration phase in order to successfully reach and grasp the object agrees with previous research (Mateo et al., 2013, Hoffmann et al., 2006, de los Reyes-Guzmán et al., 2010, Laffont et al., 2000), but extends the notion of the importance of the final adjustment phase (Coats and Wann, 2011) from the non-injured to cSCI population. From previous research it was expected that the OA would produce a longer final adjustment phase than YA, but this did not reach significance, which may be due to the task in the present study not involving specific object placement or end point accuracy (Coats and Wann, 2011). The increased number of adjustments (figure 6.2a-b and 6.8a-b) is also consistent with previous research as participants with an icSCI showed an increase in the number of small but multiple accelerations, i.e. adjustments, of the upper limb compared to non-injured control participants (Koshland et al., 2005).

Previous research in older adults has suggested that a decrease in proprioceptive abilities (Sosnoff and Newell, 2006) reduces online control of movement, and induces a greater number of adjustments and time spent in the deceleration phase for successful task completion, as feedback comes from other sources such as vision (Coats and Wann, 2012). In the present study, this is supported as OA produced a longer propDT than YA. Thus, one plausible explanation of the present data is that due to declines in proprioceptive abilities participants with an icSCI produced a greater number of adjustments, prolonged deceleration phase and prolonged final adjustment phase in order to correct errors when they can visually fixate the limb and object in relation to one another, i.e. late in the movement. The limb by group interaction that emerged (in experiment one) for the number of adjustments in the final adjustment phase showed that participants with an icSCI made more adjustments with the MI limb than LI limb. This agrees with the increased reliance on visual feedback, as the MI limb suffers more sensory and proprioceptive deficit and thus more adjustments are needed when visual feedback is available (late in the movement). Overall, this suggestion is supported further by research in deafferented patients (loss of proprioception), as the removal of vision resulted in less accurate reaching movements (Gordon et al., 1995). Future research that manipulates visual feedback when reaching and grasping will give further insight into the role of vision following icSCI.

In both experiments participants with an icSCI produced a greater resultant path length than OA, with the additional group difference to YA in experiment two (figures 6.4a and 6.10a). This suggests that participants with an icSCI induced errors in the trajectory of the upper limb towards the object when compared to YA and OA (who follow a direct path to the object). This could have occurred due to declines in control of proximal and distal muscles during the reach, due to injury of the CST (Lemon et al., 1995). Alternatively, it could have emerged due to loss of proprioceptive information regarding limb position, supported by an increased number of adjustments and time spent in propDT and propFAP. In experiment one and two participants with an icSCI produced movements with an increased wrist height when compared to YA (figure 6.4c and 6.10c), which agrees with previous research (de los Reyes-Guzmán et al., 2010, Mateo et al., 2013, Hoffmann et al., 2006, Laffont et al., 2000), and is postulated to occur in order to prevent object collision as the hand arrives above the object (de los Reyes-Guzmán et al., 2010). The increased wrist height might have contributed to the increase in resultant path length.

In agreement with previous research, peak velocity (figure 6.1b) was greater when moving to the far than near object (experiment one) (Jakobson and Goodale, 1991, Bootsma et al., 1994). Movement to the near object required more deceleration (Jeannerod, 1981) and time in the final adjustment phase than movement to the far object, however, this was not accompanied by a significant difference in movement time (for all participants, figure 6.1b and 6.1c). The increased deceleration (propDT and propFAP) seen towards the near object may be a strategy to avoid object collision, and to allow precise finger and thumb placement around the object (Lommertzen et al., 2009). In previous research object collision avoidance has been shown to influence both movement duration (increase movement time), which is not supported by the findings in the current study, and maximum grasp aperture (increase maximum grasp aperture), which holds true for participants with an icSCI in the current study when compared to YA (see section 6.5.7) (Mon-Williams et al., 2001).

The main effect of distance did not reach significance for the number of adjustments in the approach phase (figure 6.2a), but in the final adjustment phase (figure 6.2b) more adjustments were made when reaching to the near than far object for participants with an icSCI and OA, but not YA as shown by the distance by group interaction. This is not consistent with previous research as generally more adjustments are made when a higher peak velocity is reached, which in this case was for the far object (Fradet et al., 2008). However, more adjustments are often made when accuracy requirements of the task are greater, as suggested by Fradet et al., (2008). In this case, the greater number of adjustments seen in the final adjustment phase for participants with an icSCI and OA when moving to the near object may be due to the accuracy demands of object collision avoidance (see above). Previous research has shown that individuals with a cSCI have a reduction in their workspace, i.e. reach distance, due to triceps brachii paralysis, suggesting that the far object condition should have provided an increased task difficulty and need for error correction compared to the near object condition (Robinson et al., 2010).

In experiment two, a size by group interaction emerged for movement time (figure 6.7a) and propFAP (figure 6.7c) and subsequent analysis revealed that participants with an icSCI produced movements of a longer duration and with a prolonged final adjustment phase (with more adjustments made) when moving to the large object than the small object, with no difference between object conditions in YA or OA. This may be because participants with an icSCI have a reduced MGA (Stahl et al., 2014), thus have a lower safety margin (difference between MGA and object size) for successful grasp of larger objects and avoidance of object collision when compared to non-injured participants. Therefore the prolonged movement time, propFAP and number of adjustments when reaching to the large object may be a strategy to ensure successful finger and thumb placement around the object. Introducing surface friction to the object (increasing object texture) may diminish this group difference between participants with an icSCI and non-injured participants. This is because increasing object friction has been shown to provide a larger zone for effective grasping in older adults, who also show a reduced MGA compared to younger adults as hand mobility is understood to decline with age (Holt et al., 2013). The difference in MGA characteristics between YA and OA may not have emerged in the present study, as the large object was only 6cm in diameter to ensure participants with an icSCI could complete the task. In other non-injured studies the larger objects have been up to 9cm (Bootsma et al., 1994, Holt et al., 2013).

Object size influenced peak muscle activity in relation to kinematic events for the anterior deltoid only (shoulder flexor and medial rotator), with a size by group interaction showing that this was for participants with an icSCI. This provides support for previous research as participants with a cSCI have been shown to rely more heavily on the shoulder complex to perform reaching movements (to produce passive elbow extension) (Koshland et al., 2005, Janssen-Potten et al., 2008, Jacquier-Bret et al., 2009). Further analysis of the interaction showed that peak anterior deltoid activity was closer to PV when reaching for the small object, and closer to the start of FAP when reaching for the large object. In addition, although not significant, the agonist-antagonist muscle activity between the triceps brachii and biceps brachii was also weaker in the large object condition for participants with an icSCI. Thus, an increased reliance on the anterior deltoid may have been necessary to slow the limb down when reaching for the large object (apply a braking force) and prevent further extension of the arm, which is usually carried out by the biceps brachii (Hughes et al., 2009). Further research including more muscles of the shoulder complex would support this theory, as participants with a cSCI have already been shown to rely more heavily on the shoulder flexors (anterior deltoid and pectoralis major) when performing reaching movements compared to non-injured participants (who show reciprocal patterns between the shoulder flexors/extensors and elbow flexors/extensors) (Koshland et al., 2005).

6.7.2 Grasp phase

With regards to the grasp phase, in experiment one there was a significant distance by group interaction for MGA (figure 6.3a), which showed that MGA was larger for the near object for participants with an icSCI but OA had larger MGA for the far object. Additionally, for the near object condition (small object condition in experiment two) participants with an icSCI formed a larger MGA than YA, but the group difference did not remain for the far object. MGA was also reached earlier in the movement (figure 6.3b) by participants with an icSCI compared to YA, and for all participants occurred earlier when reaching for the near object compared to the far object, which coincides with the longer deceleration and final adjustment phase in the near object condition. The larger MGA formation (increased safety margin) for participants with an icSCI and OA, and earlier MGA formation for participants with an icSCI may be compensatory mechanism to allow for corrections of finger and thumb placement around the object when performing the precision grip (Marteniuk et al., 1990), and avoidance of object collision (Mon-Williams et al., 2001). Additionally, the earlier MGA formation may have contributed to the temporal dissociation between the transport and grasp phases when compared to YA and OA seen in both experiments (figure 6.3c and 6.9c), which agrees with previous research in that the transport and grasp phases are planned and performed sequentially following cSCI (Mateo et al., 2013). For future work, introducing object friction might reduce the larger and earlier MGA formation seen, as increasing surface friction has been shown to increase the effective zone of finger placement in older adults and therefore reduces the amount of error susceptible in finger placement around the object (Holt et al., 2013).

In experiment two the grasp phase results showed that all participants were able to scale their MGA to object size as larger MGA's were produced when reaching to the large compared to the small object (figure 6.9a). This is in agreement with research by Stahl et al., (2014), as despite reduced MGA participants with a cSCI could still scale their hand opening to object size. A size by group interaction for MGA showed that for the large object there was no significant difference between groups, but for the small object participants with an icSCI produced a larger MGA than YA. This suggests that participants with an icSCI could be producing MGA's close to their maximum given their injury, hence no group differences arose in the large object condition. Participants with an icSCI produced MGA earlier in the movement compared to YA and OA (figure 6.9b), which resulted in the transport and grasp phases becoming less coupled (figure 6.9c). Object size also influenced coupling of the transport and grasp phases of prehension as reaching to the large object resulted in greater decoupling than reaching to the small object. Although not significant, this decoupling was more pronounced for participants with an icSCI (figure 6.9c) suggesting that the hand was opened to MGA before the limb started to decelerate. This supports their use of the decelerative and final adjustment phase for accurate finger and thumb placement around the object when reaching for the large object.

Overall the group differences seen between participants with an icSCI and non-injured participants, e.g. larger MGA formation, earlier hand opening and increased propFAP, may be due to disruption of the CST, which has been shown to detriment preshaping of the hand in primates (Sasaki et al., 2004). The direct CM network of the CST, as well as premotor spinal interneurons, have also shown activation during the dynamic phase (squeezing the index finger and thumb together) of the precision grip (Bennett and Lemon, 1996, Takei and Seki, 2013) (see chapter 2, sections 2.2 and 2.4). Thus, disruption of these pathways following icSCI may have resulted in detriments in grip force modulation. Therefore, participants with an icSCI within the study could have spent a longer proportion of movement time in the final adjustment phase in order to allow more time to ensure successful grip around the object. In addition, force modulation during the precision grip has already been shown to decline with age (Voelcker-Rehage and Alberts, 2005), and as the participants with an icSCI were often older adults this adds to the possibility that declines in force modulation resulted in a greater propFAP. The addition of force transducers on the object surface in future research, would give further insight into this control.

6.8 Conclusion

This study used kinematic and EMG analyses to quantify upper limb control during the acute stages of icSCI. Overall the results showed that following icSCI, movements are longer (in duration) and slower (lower peak velocity) with an increased reliance on the deceleration and final adjustment phases, which is likely to be due to loss of proprioceptive feedback following injury to the cervical spinal cord. Additionally, participants with an icSCI show a tendency to produce a MGA larger than the object size and earlier in the movement, which are both compensatory strategies to increase the opportunity for error correction in order to ensure accurate finger and thumb placement around the object.

With regards to the EMG results, participants with an icSCI showed novel muscle activity patterns in order to apply a braking force to the upper limb when compared to non-injured participants. This may have emerged due to loss of agonist-antagonist muscle activity between the triceps brachii and biceps brachii. This novel muscle activity pattern suggests that neuroplasticity and reorganisation of the spared pathways following icSCI has occurred, in order for the reach to grasp movement to be performed.

Finally, object properties (distance and size) influenced the transport and grasp phases of unimanual prehension following icSCI, and in particular objects that are close to the individual and large in size present greater task difficulty. This increase in task difficulty manifests itself in clear control differences between people with an icSCI and non-injured individuals e.g. longer movement time, increased reliance on the final adjustment phase and earlier hand opening. In relation to the remainder of this thesis the following chapters will address if and how object distance and object size influence bimanual coordination after icSCI when compared to non-injured YA and OA.

Chapter 7 Study two

7.1 Introduction

Many activities of daily living require the use of both hands simultaneously, thus providing a basic rationale for the use of bimanual therapy following injury to the cervical spinal cord. In addition, pilot research has supported the use of bimanual therapy for improving bimanual upper limb function following cSCI (Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2010). However, to date there has been no research that has quantified how people with a cSCI reach and grasp objects bimanually despite bimanual deficits following cSCI (Cacho et al., 2011), which will give insight into how control of bimanual movements changes and help to guide rehabilitation.

In the non-injured population most research has focused on how symmetrical (reaching and grasping objects at the same distance or size) and asymmetrical bimanual tasks (reaching and grasping objects at different distances or sizes) influence kinematic characteristics of bimanual movements and synchrony between the limbs (see chapter 3, section 3.3.1 and 3.3.2). Overall, object size and object distance influence the transport and grasp phases in a similar fashion to unimanual conditions e.g. greater peak velocity in far object conditions. With regards to interlimb synchrony, some research supports the notion of synchrony between the limbs, whereas, other research has questioned this synchrony by finding temporal differences, especially during asymmetrical bimanual tasks (Riek et al., 2003, Mason and Bruyn, 2009, Bingham et al., 2008). This asynchrony between limbs is postulated to arise due to visual constraints (Riek et al., 2003, Mason and Bruyn, 2009), which may be exaggerated in participants with an icSCI due to their declines in motor and sensory function (see chapter 3, section 3.3.2).

The current study comprises two experiments, which aim to examine bimanual prehension following icSCI and how this differs to non-injured YA and OA. The first experiment focuses on object distance and the second experiment on object size with both comparing symmetric and asymmetric conditions. The study tests the following hypotheses; (1) participants with an icSCI will produce longer (duration), slower (lower peak velocity), less smooth movements than non-injured YA and OA, (2) muscle activity patterns will differ between participants with an icSCI and non-injured YA and OA, (3) participants with an icSCI will produce less synchronous movements than non-injured YA and OA due to declines in sensory and motor function.

7.2 Methods

7.2.1 Participants

Eighteen participants (table 5.0) with an icSCI (Mean age=61.61 ±15.24 years, 14 right handed), sixteen younger adults (Mean age=23.6±4.54 years, 14 right handed) and sixteen older adults (Mean age=71±7.2 years, 12 right handed) volunteered for participation in this study. Further details can be found in chapter 5 (section 5.2.1).

7.2.2 Task

All details regarding the specifics of the task are presented in chapter 5 (section 5.3.2). As experiment one was concerned with object distance the objects were placed at 50% (near) or 70% (far) of each participant's maximal reach distance. Therefore there were four blocks of eight trials (two symmetrical and two asymmetrical) for experiment one (figure 7.0 a-d); Preferred/Less Impaired limb (P/LI) Near Non-preferred/More Impaired limb (NP/MI) Near (NN), P/LI limb Far NP/MI limb Far (FF), P/LI limb Near NP/MI limb Far (NF), P/LI limb Far NP/MI limb Near (FN). As experiment two was concerned with object size (large and small), the objects were placed at the near distance so as not to manipulate both object distance and object size at the same time. Thus, there were four blocks of eight trials (two symmetrical and two asymmetrical) for experiment two; P/LI Small NP/MI Small (SS), P/LI Large NP/MI Large (LL), P/LI limb Small NP/MI limb Large (SL), P/LI limb Large NP/MI limb Small (LS).

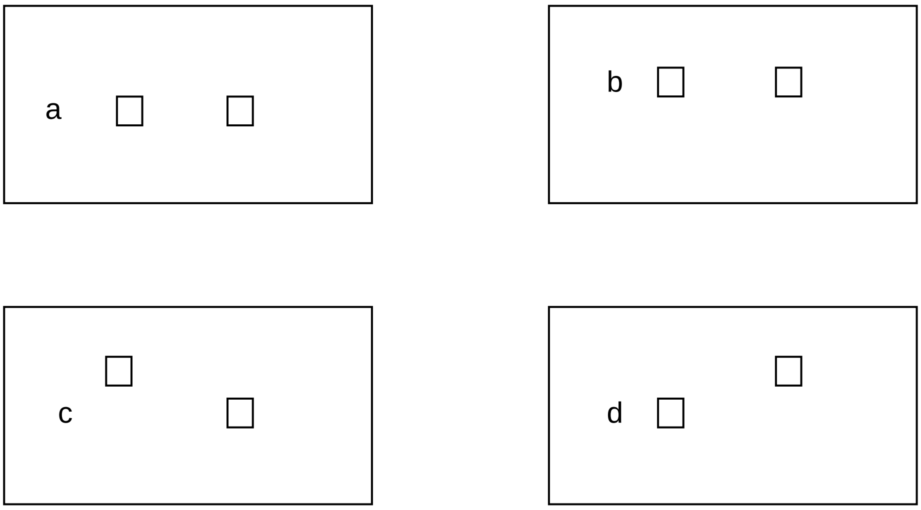

Figure 7.0: Drawn depiction of the experimental set up. (Four blocks of bimanual trials in experiment one if the participant's P/LI limb is right; P/LI Near NP/MI Near (a, NN), P/LI Far NP/MI Far (b, FF), P/LI Near NP/MI Far (c, NF), P/LI Far NP/MI Near (d, FN)).

7.2.3 Dependent variables and statistical analysis

A full description of procedures for the kinematic and EMG analyses, in addition to as the dependent variables is presented in chapter 5 (section 5.3.3 and 5.3.4). To analyse the kinematic and EMG data a series of mixed repeated measures ANOVA's were performed for each dependent variable. This analyses permitted exploration of the main effects of group (3 – icSCI, YA, OA), distance (4 – NN, FF, NF, FN) and limb (2 – P/LI, NP/MI) for experiment one, and group (3 – icSCI, YA, OA), size (4 – SS, LL, SL, LS) and limb (2 – P/LI, NP/MI) for experiment two. To investigate interlimb synchrony a series of repeated measures ANOVAs were performed to permit the exploration of the main effect of group and distance in experiment one, and group and size in experiment two.

To investigate a condition by group interaction limb was collapsed and one-way ANOVAs were performed for each condition in order to determine any significant differences between groups. Following this, repeated measures ANOVAs were performed for each group to explore the main effect of condition. In the event of a condition by limb interaction group was collapsed and repeated measures ANOVAs for each limb were performed to explore the main effect of condition. In addition, paired t-tests were performed for each condition in order to determine the significance levels of differences between the limbs. Finally, to investigate a limb by group interaction condition was collapsed and one-way ANOVAs were performed for each limb to determine any significant group differences. Paired t-tests were also performed for each group to decipher whether the difference between limbs reached significance.

7.3 Results for experiment one – Kinematic data

7.3.1 Movement time

As shown in figure 7.1a participants with an icSCI (M=1850ms) produced movements of a longer duration than YA (M=781ms) and OA (M=995ms) [$F(2,42)=24.95$, $p<0.001$, $\eta^2=0.54$] with no significant difference between YA and OA ($p>0.05$). There was a significant main effect of condition [$F(3,40)=4.97$, $p<0.05$, $\eta^2=0.27$] as movement time (MT) for condition two (FF, M=1274ms) was significantly longer than condition four (FN, M=1175ms). There was no significant difference between any of the other conditions ($p>0.05$). The main effect of limb did not reach significance [$F(1,42)=0.88$, $p>0.05$, $\eta^2=0.02$] and no significant interactions emerged.

7.3.2 Peak velocity

In agreement with the longer MT participants with an icSCI (M=541mm/s) reached a lower peak velocity (PV) than YA (M=826mm/s) and OA (M=709mm/s) [$F(2,42)=15.10$,

$p<0.001$, $\eta^2=0.42$] presented in figure 7.1b, with no significant difference emerging between YA and OA ($p>0.05$). A significant main effect of condition also emerged [$F(3,40)=53.47$, $p<0.001$, $\eta^2=0.80$] as PV in condition one (NN, M=607mm/s) was significantly lower than PV in condition two (FF, M=765mm/s), three (NF, M=704mm/s) and four (FN, M=693mm/s). Additionally, PV in condition two (FF) was significantly greater than condition three and four ($p<0.05$). There was no significant difference between conditions three and four ($p>0.05$). The main effect of limb did not reach significance [$F(1,42)=0.43$, $p>0.05$, $\eta^2=0.01$]. However, a significant condition by group interaction emerged [$F(6,80)=3.61$, $p<0.01$, $\eta^2=0.21$] and a significant condition by limb interaction emerged [$F(3,40)=169.95$, $p<0.001$, $\eta^2=0.93$]. These will be explored in further detail below.

To investigate the condition by group interaction, repeated measures ANOVAs (limb collapsed) for each group were performed. The results revealed that for participants with an icSCI [$F(3,14)=4.84$, $p=0.016$, $\eta^2=0.51$], YA [$F(3,13)=30.05$, $p<0.001$, $\eta^2=0.88$] and OA [$F(3,9)=74.57$, $p<0.001$, $\eta^2=0.96$] there was a significant main effect of condition. Post-hoc analysis revealed that for participants with an icSCI PV in condition one (NN=506mm/s) was significantly lower than in condition two (FF, 587mm/s) but there was no significant difference between the other conditions ($p>0.05$). For YA, PV was significantly lower in condition one (NN=702mm/s) compared to condition two (FF=918mm/s) and four (FN=838mm/s). A higher PV was also reached in condition two compared to condition three (NF=541mm/s) and four ($p<0.05$). Finally for YA, PV in condition three was significantly lower than condition one ($p<0.05$). There was no significant difference between condition three and four ($p>0.05$). For OA, PV in condition one (NN=613mm/s) was significantly lower than that of condition two (FF=791mm/s), three (NF=722mm/s) and four (FN=709mm/s). PV in condition two was also significantly higher than condition three and four ($p<0.05$). There was no significant difference between condition three and four ($p>0.05$).

Following this, one-way ANOVAs for each condition (to determine group differences) were performed. For all conditions there was a significant main effect of group (NN [$F(2,48)=9.06$, $p<0.001$, $\eta^2=0.28$], FF [$F(2,49)=18.82$, $p<0.001$, $\eta^2=0.45$], NF [$F(2,46)=15.96$, $p<0.001$, $\eta^2=0.42$], FN [$F(2,48)=18.10$, $p<0.001$, $\eta^2=0.44$]). In condition one (NN) participants with an icSCI (M=494mm/s) reached lower PV than YA (M=702mm/s). In condition two (FF), three (NF) and four (FN) participants with an icSCI (FF=572mm/s, NF=541mm/s, FN=522mm/s) reached a lower PV than both YA (FF=918mm/s, NF=849mm/s, FN=838mm/s) and OA (FF=795mm/s, NF=724mm/s, FN=718mm/s). For all conditions there was no significant difference in PV between YA and OA ($p>0.05$).

To investigate the condition by limb interaction, firstly, repeated measures ANOVAs (group collapsed) were performed for each limb. For the P/LI limb there was a significant main effect of condition [$F(3,42)=43.67$, $p<0.001$, $\eta^2=0.76$] as PV was lower in condition one (NN=601mm/s) compared to condition two (FF=759mm/s) and condition four (FN=761mm/s). Additionally, PV in condition two (FF) and four (FN) was higher than in condition three (NF=612mm/s). There was no significant difference between condition one and three or two and four ($p>0.05$). For the NP/MI limb there was also a significant main effect of condition [$F(3,42)=64.27$, $p<0.001$, $\eta^2=0.82$] as PV was lower in condition one (NN=608mm/s) compared to condition two (FF=758mm/s, $p<0.001$) and three (NF=785mm/s, $p<0.001$). PV in condition two (FF) and three (NF) was also significantly higher than in condition four (FN=614mm/s).

Paired t-tests for each condition were carried out to decipher any significant differences in PV between limbs. For the symmetrical conditions (condition one and two) there was no significant difference in PV between limbs (NN [$t(48)=-0.62$, $p>0.05$], FF [$t(49)=-0.02$, $p>0.05$]). However, for the asymmetrical conditions (condition three and four) there was a significant difference in PV between limbs (NF [$t(46)=-12.90$, $p<0.001$], FN [$t(48)=12.17$, $p<0.001$]). In condition three (NF) and four (FN) the limb reaching for the far object (NP/MI limb in condition three (M=786mm/s) and P/LI limb in condition four (M=759mm/s)) reached a greater PV than the limb reaching for the near object (P/LI limb in condition three (M=614mm/s), NP/MI limb in condition four (M=611mm/s)).

7.3.3 Proportion of movement time spent decelerating

Participants with an icSCI (M=76.88%) displayed a higher proportion of the movement time decelerating (propDT) than YA (M=61.35%) and OA (M= 69.02%) [$F(2,42)=39.62$, $p<0.001$, $\eta^2=0.65$]. There was also a significant difference between YA and OA ($p<0.05$) (figure 7.1c). The main effect of condition reached significance [$F(3,40)=4.88$, $p<0.01$, $\eta^2=0.26$] as a lower propDT was evident in condition four (FN=68.20%) compared to condition three (NF=69.48%, $p<0.05$). There was no significant difference between the other conditions ($p>0.05$). There was no significant main effect of limb [$F(1,42)=0.46$, $p>0.05$, $\eta^2=0.001$] but a condition by limb interaction emerged [$F(3,40)=18.96$, $p<0.001$, $\eta^2=0.59$].

To investigate the condition by limb interaction repeated measures ANOVAs (group collapsed) were undertaken to determine whether the main effect of condition reached significance for each limb. For the P/LI limb there was a significant main effect of condition [$F(3,42)=24.85$, $p<0.001$, $\eta^2=0.64$]. This was because propDT for condition four (FN=67.06%) was significantly lower than for condition one (NN=69.35%, $p=0.009$), condition two (FF=69.41%, $p=0.001$) and condition three (NF=70.69%, $p<0.001$). For the NP/MI limb the main effect of condition did not reach significance [$F(3,42)=1.44$, $p>0.05$, $\eta^2=0.09$] as propDT for all conditions was similar.

Paired t-tests were carried out to determine whether there was a significant difference between limbs for each condition. For the symmetrical conditions (condition one and two) there was no significant difference in propDT between limbs (NN [$t(48)=-0.82$, $p>0.05$], FF [$t(49)=0.88$, $p>0.05$]). However, for the asymmetrical conditions (condition three and four) there was a significant difference between limbs (NF [$t(46)=3.08$, $p<0.01$], FN [$t(48)=-3.203$, $p<0.01$]). This was because the limb reaching to the far object (NP/MI limb in condition three (M=68.62%), P/LI limb in condition four (M=67.30%)) had a lower propDT than the limb reaching for the near object (P/LI limb in condition three (M=70.55%), NP/MI limb in condition four (M=70.29%)).

7.3.4 Proportion of movement spent in the final adjustment phase

Participants with an icSCI (M=34.03%) produced movements with a longer proportion of the movement spent in the final adjustment phase (propFAP) than YA (M=10.56%) and OA (M=18.58%) (figure 7.1d) [$F(2,42)=24.97$, $p<0.001$, $\eta^2=0.54$]. There was no significant difference between YA and OA ($p>0.05$). There was also a significant main effect of condition [$F(3,40)=4.01$, $p<0.05$, $\eta^2=0.23$] as propFAP for condition two (FF=19.29%) was significantly lower than condition one (NN=22.56%). No significant main effect of limb emerged [$F(1,42)=2.06$, $p>0.05$, $\eta^2=0.05$] but there was a significant condition by limb interaction [$F(3,40)=22.30$, $p<0.001$, $\eta^2=0.63$].

To investigate the condition by limb interaction repeated measures ANOVAs (group collapsed) were performed to determine whether the main effect of condition reached significance for each limb. For the P/LI limb there was a significant main effect of condition [$F(3,42)=9.91$, $p<0.001$, $\eta^2=0.41$] as condition one (NN=23.26%) had a higher propFAP than condition two (FF=20.31%) and four (FN=18.49%). Additionally, propFAP was higher in condition three (NF=26.10%) than condition two and four. There was no significant difference between condition two and four ($p>0.05$). For the NP/MI limb there was also a significant main effect of condition [$F(3,42)=4.74$, $p<0.01$, $\eta^2=0.25$] as propFAP for condition two (FF=19.26%) and condition three (NF=18.95%) was significantly lower than condition four (FN=23.60%).

Paired t-tests (to determine any significant differences between limbs for each condition) revealed that for the symmetrical conditions (condition one and two) there was no significant difference between limbs (NN [t(48)=0.47, p>0.05], FF [t(49)=1.42, p>0.05]). However, for the asymmetrical conditions (conditions three and four) there was a significant difference between limbs [NF [t(46)=5.26, p<0.001] FN [t(48)=-4.17, p<0.001]]. This occurred as the limb reaching to the near object (P/LI limb in condition three (M=26.18%), NP/MI limb in condition four (M=25.51%)) produced a greater propFAP than the limb moving to the far object (NP/MI limb in condition three (M=19.34%), P/LI limb in condition four (M=20.95%)).

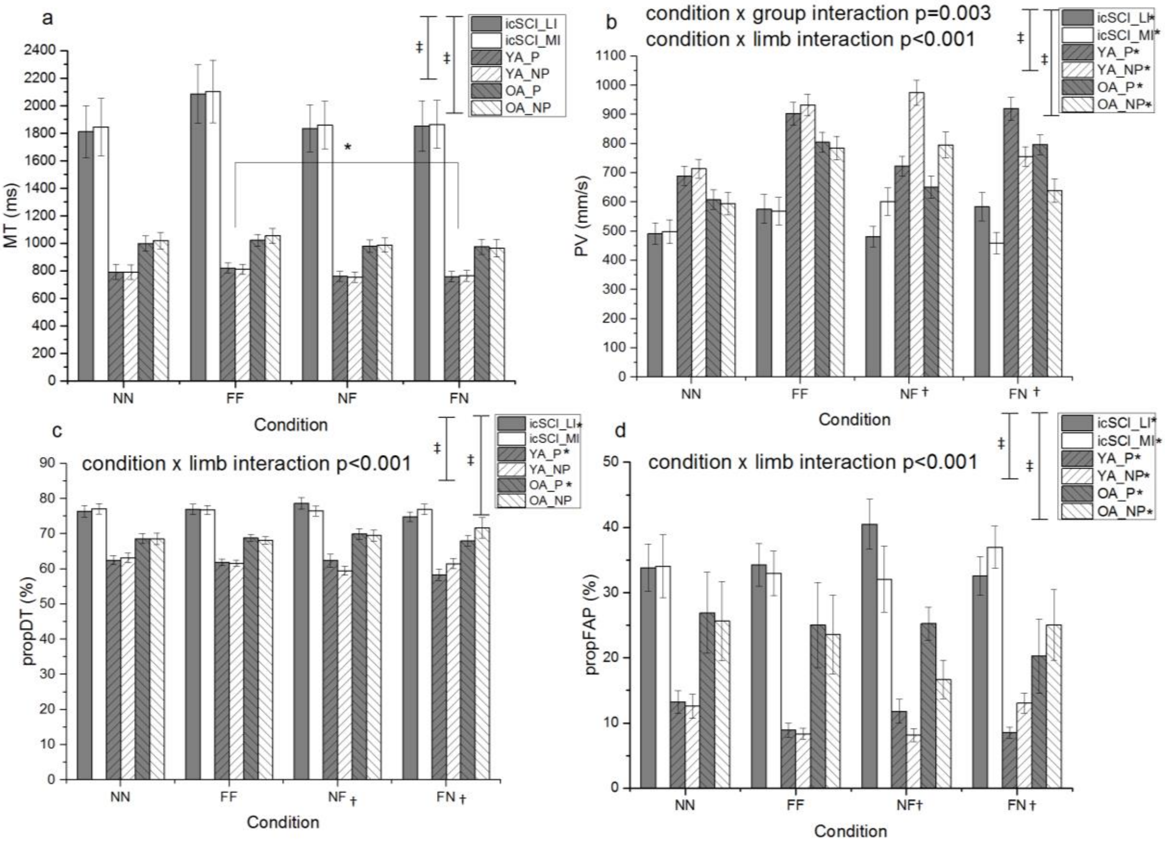

Figure 7.1: Group and limb means (±standard error) for movement time (MT) (a), peak velocity (PV) (b), proportion of movement time spent decelerating (propDT) (c) and proportion of movement time spent in the final adjustment phase (propFAP) (d) in each condition (NN, FF, NF, FN). (* denotes significant difference between conditions, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-

preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.3.5 Number of adjustments in the approach phase

As evident in figure 7.2a there was a significant main effect of group [$F(2,42)=26.40$, $p<0.001$, $\eta^2=0.56$] as participants with an icSCI (M=4.24) made more adjustments than YA (M=0.43) and OA (M=1.39). There was no significant difference between YA and OA ($p>0.05$). The main effects of condition [$F(3,40)=0.961$, $p>0.05$, $\eta^2=0.07$] and limb [$F(1,42)=1.84$, $p>0.05$, $\eta^2=0.04$] did not reach significance and no significant interactions emerged.

7.3.6 Number of adjustments in the final adjustment phase

The significant main effect of group continued into the final adjustment phase (figure 7.2b) [$F(2,42)=12.39$, $p<0.001$, $\eta^2=0.37$] as participants with an icSCI (M=8.68) made more adjustments than YA (M=1.10) and OA (M=2.24). There was no significant difference between YA and OA ($p>0.05$). The main effects of condition [$F(3,40)=0.66$, $p>0.05$, $\eta^2=0.05$] and limb [$F(1,42)=0.02$, $p>0.05$, $\eta^2=0.001$] did not reach significance, but a significant condition by limb interaction emerged [$F(3,40)=8.40$, $p<0.001$, $\eta^2=0.39$].

To investigate the condition by limb interaction paired t-tests (group collapsed) were performed to determine whether any significant difference between limbs emerged for each condition. For the symmetrical conditions (condition one and two) there was no significant difference between the P/LI and NP/MI limb (NN [$t(48)=-0.44$, $p>0.05$; FF [$t(49)=-0.95$, $p>0.05$]), but for the asymmetrical conditions (condition three and four) there was a significant difference between limbs (NF [$t(46)=4.11$, $p<0.001$; FN [$t(48)=-3.56$, $p<0.01$]). This was because the limb moving to the near object (P/LI limb in condition three (M=4.66), NP/MI limb in condition four (M=4.54)) produced a greater number of adjustments than the limb moving to the far object (NP/MI limb in condition three (M=3.56), P/LI limb in condition four (M=3.38)).

Repeated measures ANOVAs (to determine whether the main effect of condition reached significance for each limb) revealed that for the P/LI limb there was a significant main effect of condition [$F(3,42)=4.47$, $p<0.01$, $\eta^2=0.24$] as condition three (NF=4.81) resulted in a greater number of adjustments than condition four (FN=3.27) (as the P/LI limb reached for the near object in condition three). There was no significant difference between the other conditions ($p>0.05$). For the NP/MI limb main effect of condition did not reach significance [$F(3,42)=0.72$, $p>0.05$, $\eta^2=0.05$].

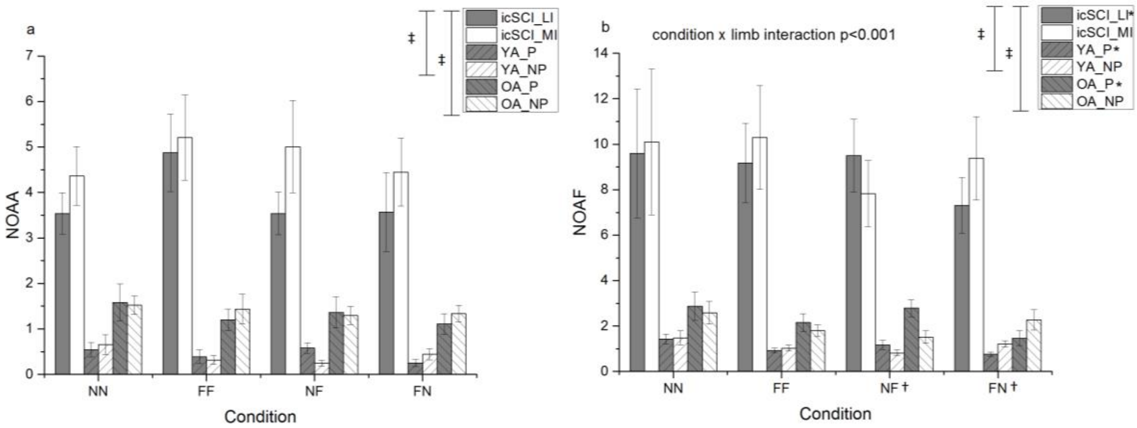

Figure 7.2: Group and limb means (±standard error) for number of adjustments in the approach phase (NOAA) (a), number of adjustments in the final adjustment phase (NOAF) (b) in each condition (NN, FF, NF, FN). (* denotes significant difference between conditions, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.3.7 Maximum grasp aperture

There was no significant main effect of group [$F(2,42)=0.01$, $p>0.05$, $\eta^2=0.001$], condition [$F(3,40)=1.613$, $p>0.05$, $\eta^2=0.108$], or limb [$F(1,42)=0.14$, $p>0.05$, $\eta^2=0.003$] (figure 7.3a). However, a significant limb by group interaction emerged [$F(2,42)=8.23$, $p<0.01$, $\eta^2=0.28$]. Subsequent one-way ANOVAs (condition collapsed) were performed to determine whether the difference between groups reached significance for each limb. For the P/LI limb [$F(2,49)=3.30$, $p>0.05$, $\eta^2=0.001$] and NP/MI limb [$F(2,49)=0.82$, $p>0.05$, $\eta^2=0.001$] there was no significant difference between groups.

Paired t-tests (to determine whether the difference between limbs reached significance) revealed that for the YA there was no significant difference between the P and NP limb [$t(15)=-1.19$, $p>0.05$], but there was a significant difference between limbs for the participants with an icSCI [$t(17)=2.51$, $p<0.05$] and OA [$t(15)=-2.72$, $p<0.05$]. For the participants with an icSCI a smaller MGA was reached for the MI (M=9.52cm) compared to LI (M=10.19cm) limb, whereas, for the OA a smaller MGA was reached for the P (M=9.59cm) compared to NP (M=9.91cm) limb.

7.3.8 Time of maximum grasp aperture as a percentage of movement time

As shown in figure 7.3b a significant main effect of group emerged [$F(2,42)=13.03$, $p<0.001$, $\eta^2=0.38$] as participants with an icSCI (M=51.95%) reached MGA earlier in the movement than YA (M=62.70%). There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). There was also a significant main effect of condition [$F(3,40)=3.39$, $p<0.05$, $\eta^2=0.20$] as MGA was reached significantly earlier in condition one (NN, M=55.28%) than condition two (FF, M=59.27%). There was no significant difference between the other conditions ($p>0.05$). The main effect of limb did not reach significance [$F(1, 42)=0.13$, $p>0.05$, $\eta^2=0.001$] but a significant limb by group interaction [$F(2,42)=6.48$, $p<0.05$, $\eta^2=0.24$] and condition by limb interaction emerged [$F(3,40)=29.20$, $p<0.001$, $\eta^2=0.69$].

To address the limb by group interaction subsequent paired t-tests (condition collapsed) were performed to investigate if the difference between the two limbs reached significance for each group. For the participants with an icSCI [$t(17)=-1.970$, $p>0.05$] and OA [$t(15)=1.574$, $p>0.05$] there was no significant difference between limbs. However, for the YA [$t(15)=3.027$, $p<0.01$] there was a significant difference as MGA for the NP (M=61.06%) limb was reached earlier in the movement compared to the P (M=64.33%) limb.

One-way ANOVAs (to investigate whether the difference between groups reached significance for each limb) revealed that for the P/LI [$F(2,49)=20.82$, $p<0.001$, $\eta^2=0.47$] and NP/MI limb [$F(2,49)=3.89$, $p<0.05$, $\eta^2=0.14$] there was a significant difference between groups as participants with an icSCI (LI=48.79%, MI=53.86%) reached MGA earlier in the movement than YA (P=64.33%, NP=61.06%). For the P/LI limb participants with an icSCI also reached MGA earlier in the movement than OA (P=57.51%) but this difference between groups did not occur for the NP/MI limb ($p>0.05$). Additionally, for the P limb YA reached MGA earlier in the movement than OA ($p<0.05$), but this group difference did not occur for the NP limb ($p>0.05$).

To investigate the condition by limb interaction (group collapsed) paired t-tests were performed to determine whether the difference between the limbs reached significance for each condition. For the symmetrical conditions (condition one and two) there was no significant difference between limbs (NN [$t(48)=0.03$, $p>0.05$]; FF [$t(49)=-0.12$, $p>0.05$]). For the asymmetrical conditions (condition three and four) there was a significant difference between limbs (NF [$t(46)=-2.530$, $p<0.05$]; FN [$t(48)=2.790$, $p<0.05$]). This was because the limb reaching for the near object (P/LI limb in condition three (M=54.05%), NP/MI limb in condition four (M=54.58%)) reached MGA earlier in the movement than the limb reaching for the far object (NP/MI limb in condition three (M=58.68%), P/LI limb in condition four (M=58.75%)).

Repeated measures ANOVAs (performed to investigate the main effect of condition on each limb) revealed that for the P/LI limb there was a significant main effect of condition [$F(3,42)=13.47$, $p<0.001$, $\eta^2=0.49$] as MGA in condition one (NN=54.82%) and three (NF=53.76%), i.e. when reaching for the near object, was reached significantly earlier than in condition two (FF=59.27%) and four (FN=59.82%). For the NP/MI limb there was also a significant main effect of condition [$F(3,42)=7.92$, $p<0.001$, $\eta^2=0.36$] as MGA was reached significantly earlier in condition one (NN=55.40%) compared to condition three (NF=59.91%, $p<0.001$), i.e. earlier when reaching for the near object in condition one compared to the far object in condition three. There was no significant difference between other conditions ($p>0.05$).

7.3.9 Transport and grasp coupling

There was no significant main effect of group [$F(2,42)=0.89$, $p>0.05$, $\eta^2=0.04$] although participants with an icSCI (M=208ms) displayed less coupled transport and grasp phases than YA (M=57ms) and OA (M=120ms) as seen in figure 7.3c. There was no significant main effect of condition [$F(3, 40)=0.14$, $p>0.05$, $\eta^2=0.01$] or limb [$F(1,42)=0.26$, $p>0.05$, $\eta^2=0.01$], however, a significant limb by group interaction emerged [$F(2, 42)=3.66$, $p<0.05$, $\eta^2=0.22$]. Subsequent one-way ANOVAs (condition collapsed) were performed for each limb to determine whether the difference between groups reached significance, and revealed that for the P/LI limb there was a significant difference between groups [$F(2,49)=10.93$, $p<0.001$, $\eta^2=0.32$] as participants with an icSCI (M=272.23ms) produced less coupled transport and grasp phases than YA (M=62.54ms) and OA (M=116.80ms). There was no significant difference between YA and OA ($p>0.05$). For the NP/MI limb there was no significant difference between groups [$F(2,49)=0.12$, $p>0.05$, $\eta^2=0.01$] although participants with an icSCI did produce less coupled movements as seen in figure 7.3c.

Paired t-tests (to determine whether a significant difference between limbs occurred for each group) revealed that for each group there was no significant difference between limbs (icSCI [$t(17)=-0.46$, $p>0.05$]; YA [$t(15)=-1.31$, $p>0.05$]; OA [$t(15)=-0.62$, $p>0.05$]).

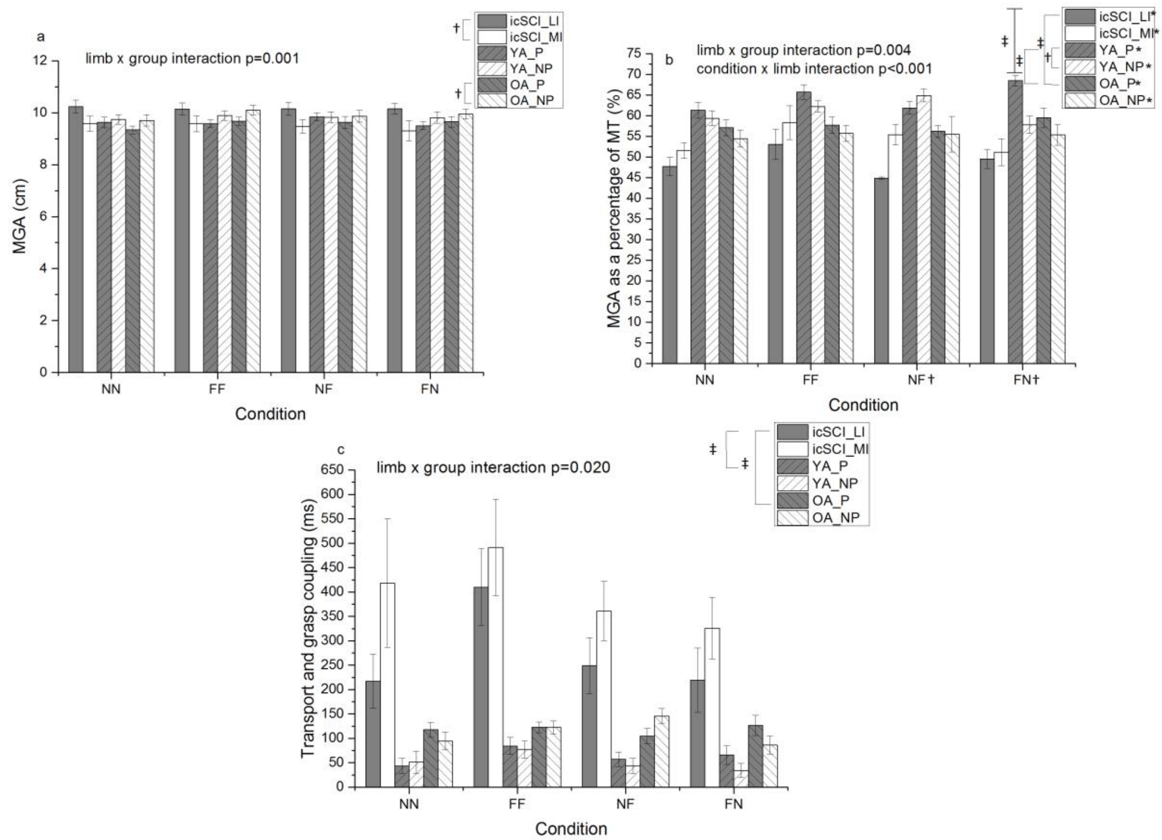

Figure 7.3: Group and limb means (±standard error) for maximum grasp aperture (MGA) (a), time of maximum grasp aperture as a percentage of movement time (MGA as a percentage of MT) (b) and transport and grasp coupling (c) in each condition (NN, FF, NF, FN). (* denotes significant difference between conditions, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.3.10 Path length

The main effects of group [$F(2,42)=2.18$, $p>0.05$, $\eta^2=0.09$] and limb [$F(1,42)=0.72$, $p>0.05$, $\eta^2=0.02$] did not reach significance. However, there was a significant main effect of condition [$F(3,40)=135.58$, $p<0.001$, $\eta^2=0.91$] (figure 7.4a) as resultant PL for condition one (NN, M=26.2cm) was significantly shorter than condition two (FF, M=35cm), condition three (NF, M=30.7cm) and condition four (FN, M=30.2cm). Also, resultant PL in condition two was significantly longer than condition three ($p<0.001$) and four ($p<0.001$) as both limbs reached for the far object. There was no significant difference between condition three and four ($p>0.05$).

A significant condition by limb interaction emerged [$F(3, 40)=125.06$, $p<0.001$, $\eta^2=0.90$] and subsequent paired t-tests (group collapsed) revealed that for the symmetrical conditions (condition one and two) there was no significant difference between limbs (NN [$t(48)=0.07$, $p>0.05$]; FF [$t(49)=-1.58$, $p>0.05$]). However, there was a significant difference for the asymmetrical conditions (NF [$t(46)=-15.81$, $p<0.001$]; FN [$t(48)=14.37$, $p<0.001$]). This was because, as expected, there was a longer resultant path length when reaching to the far object (NP/MI limb in condition three (M=34.86cm), P/LI limb in condition four (M=34.22cm)) compared to near object (P/LI limb in condition three (M=26.36cm), NP/MI limb in condition four (M=26.81cm)).

Repeated measures ANOVAs (performed for each limb to determine the main effect of condition) revealed that for the P/LI limb there was a significant main effect of condition [$F(3,42)=147.21$, $p<0.001$, $\eta^2=0.91$] as resultant PL for condition one (NN=26.6cm) and three (NF=26.6cm) was significantly shorter than condition two (FF=34.9cm) and four (FN=34.1cm). There was no significant difference between condition two and four ($p>0.05$) and these findings are consistent with the P/LI limb reaching for the far object in condition two and four. For the NP/MI limb there was also a significant main effect of condition [$F(3,42)=140.03$, $p<0.001$, $\eta^2=0.91$] as PL in condition one (NN=26.4cm) and four (FN=26.8cm) was shorter than that of condition two (FF=35.6cm, $p<0.001$) and three (NF=35.1cm, $p<0.001$). Again these findings are consistent with the NP/MI limb reaching to the far object in condition two and three.

With regards to path length in the vertical direction (z) (figure 7.4b) there was no significant main effect of group [$F(2,42)=1.94$, $p>0.05$, $\eta^2=0.09$] , condition [$F(3,40)=2.02$, $p>0.05$, $\eta^2=0.13$] or limb [$F(1,42)=0.07$, $p>0.05$, $\eta^2=0.002$] and no significant interactions emerged. Additionally, there was no significant main effect of group [$F(2,42)=2.20$, $p>0.05$, $\eta^2=0.10$], condition [$F(3,40)=2.34$, $p>0.05$, $\eta^2=0.14$] or limb [$F(1,42)=0.66$, $p>0.05$, $\eta^2=0.02$] for maximum wrist height and no significant interactions emerged (figure 7.4c).

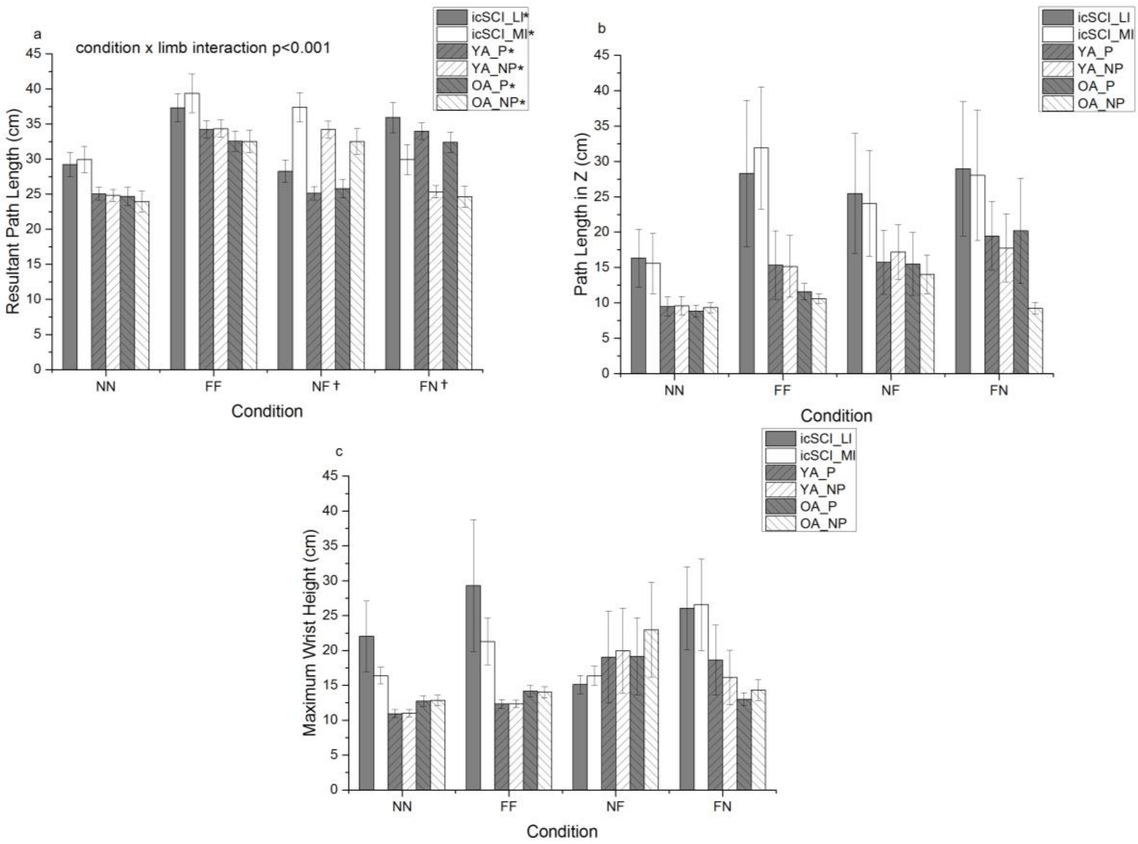

Figure 7.4: Group and limb means (±standard error) for resultant path length (a), path length in the vertical direction (z) (b) and maximum wrist height (c) in each condition (NN, FF, NF, FN). (* denotes significant difference between conditions and † reflects significant difference between the limbs), (icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.3.11 Interlimb synchrony

At the start of the movement [$F(2,42)=7.26$, $p<0.01$, $\eta^2=0.26$], peak velocity [$F(2,42)=18.92$, $p<0.001$, $\eta^2=0.47$], start of the final adjustment phase [$F(2,41)=21.11$, $p<0.001$, $\eta^2=0.51$] and end of the movement [$F(2,42)=6.08$, $p<0.01$, $\eta^2=0.23$] there was a significant main effect of group as participants with an icSCI (ST=51ms, PV=75ms, FAP=208ms, END=72ms) were less synchronous than YA (ST=17ms, PV=22ms, FAP=42ms, END=25ms) and OA (ST=25ms, PV=30ms, FAP=74ms, END=26ms) (figure 7.5 a-d). There was no significant difference between YA and OA at any of the kinematic events ($p>0.05$). There was no significant main effect of condition at the start of the movement [$F(3,40)=1.42$, $p>0.05$, $\eta^2=0.10$], peak velocity [$F(3,40)=1.17$, $p>0.05$, $\eta^2=0.08$], or end of the movement [$F(3,40)=0.60$, $p>0.05$, $\eta^2=0.04$]. However, at the start of the final adjustment phase there was a significant main effect of condition [$F(3,39)=3.56$, $p<0.05$, $\eta^2=0.22$] as condition three (M=140ms) was less synchronous than condition one (M=84ms).

A significant condition by group interaction emerged for the start of the final adjustment phase [$F(6,78)=2.65$, $p<0.05$, $\eta^2=0.17$] and subsequent repeated measures ANOVAs for each group (to determine the main effect of condition) revealed that for YA [$F(3,13)=2.59$, $p>0.05$, $\eta^2=0.37$] and OA [$F(3,8)=3.30$, $p>0.05$, $\eta^2=0.55$] there was no significant main effect of condition. However, there was a significant main effect of condition for participants with an icSCI [$F(3,14)=3.42$, $p<0.05$, $\eta^2=0.42$] but post-hoc tests revealed no significant differences between condition although the asymmetrical conditions (NF=270ms, FN=239ms) were less synchronous than the symmetrical conditions (NN=142ms, FF=183ms). One-way ANOVAs (to investigate difference between groups) for each condition (condition one NN [$F(2,48)=14.38$, $p<0.001$, $\eta^2=0.38$], condition two FF [$F(2,48)=17.89$, $p<0.001$, $\eta^2=0.44$], condition three NF [$F(2,46)=12.35$, $p<0.001$, $\eta^2=0.36$], condition four FN [$F(2,48)=7.93$, $p<0.01$, $\eta^2=0.26$]) showed that participants with an icSCI (NN=142ms, FF=190ms, NF=270ms, FN=241ms) were less synchronous than YA (NN=43ms, FF=35ms, NF=38ms, FN=52ms) and OA (NN=69ms, FF=55ms, NF=108ms, FN=72ms) .

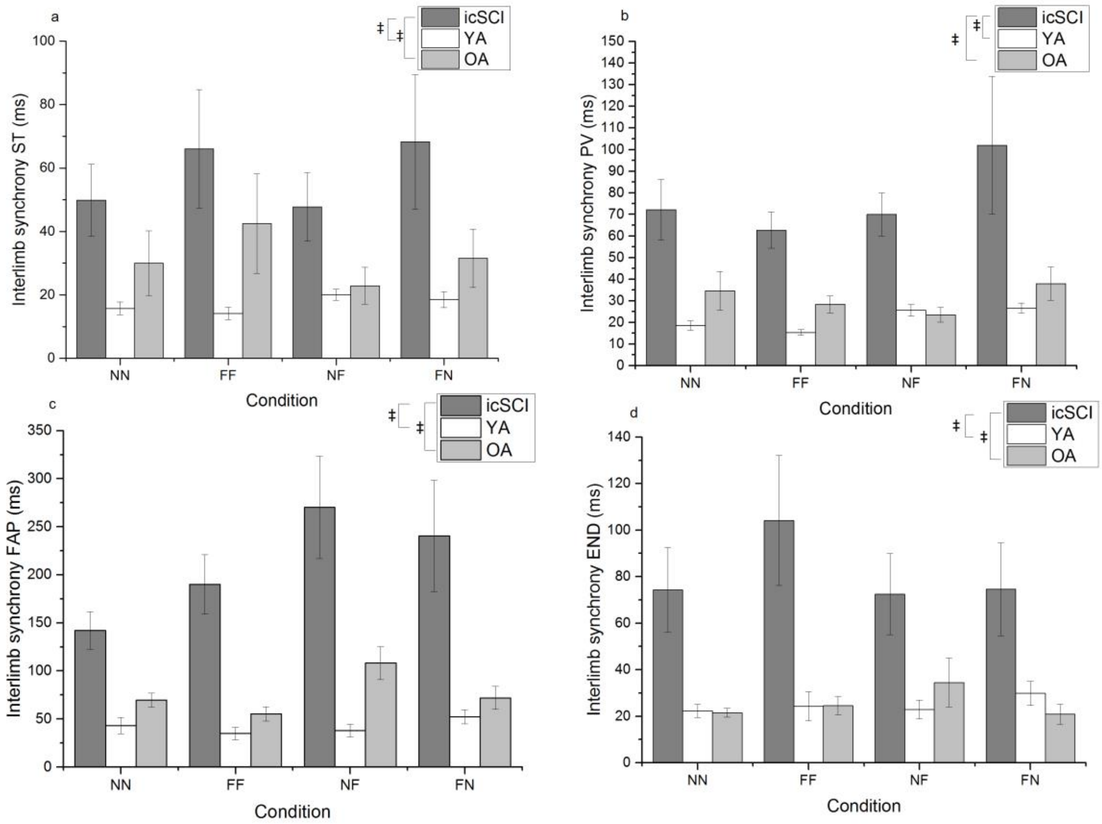

Figure 7.5: Group means (±standard error) for absolute interlimb synchrony at the start of the movement (ST) (a), peak velocity (PV) (b), start of the final adjustment phase (FAP) (c), and end of the movement (END) (d) in each condition (NN, FF, NF, FN). (‡ represents a significant difference between groups), (icSCI= dark grey, YA = white, OA = light grey, icSCI = participants with an incomplete cervical Spinal Cord Injury YA = non-injured younger adults, OA = non-injured older adults).

7.4 Electromyography analysis

For all participants timing of peak muscle activity occurs between peak velocity and the start of the final adjustment phase (as shown in table 7.0), and therefore these were the focus of subsequent statistical analyses.

7.4.1 Anterior Deltoid

In relation to peak velocity there was a significant main effect of group [$F(2,39)=14.84$, $p<0.001$, $\eta^2=0.43$] as YA (M=121ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI (M=768ms). Additionally, OA (M=352ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI. With regards to the start of FAP there was also a significant main effect of group [$F(2,39)=4.83$, $p<0.05$, $\eta^2=0.20$] as participants with an icSCI (M=50ms) produced peak anterior deltoid activity closer to the start of FAP than YA (M=261ms). There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). There was no significant main effect of condition (PV [$F(3,37)=1.77$, $p>0.05$, $\eta^2=0.13$], FAP [$F(3,37)=0.24$, $p>0.05$, $\eta^2=0.02$]) or limb (PV [$F(1,39)=0.15$, $p>0.05$, $\eta^2=0.004$], FAP [$F(1,39)=0.01$, $p>0.05$, $\eta^2=0.001$]), but for PV a significant condition by group interaction emerged [$F(6,74)=3.48$, $p<0.01$, $\eta^2=0.22$].

To investigate the condition by group interaction one-way ANOVAs (limb collapsed) were performed for each condition. For all conditions there was a significant main effect of group (condition one (NN) [$F(2,42)=5.05$, $p<0.05$, $\eta^2=0.20$], condition two (FF) [$F(2,42)=9.86$, $p<0.001$, $\eta^2=0.33$], condition three (NF) [$F(2,42)=18.27$, $p<0.001$, $\eta^2=0.48$], condition four (FN) [$F(2,42)=8.99$, $p<0.01$, $\eta^2=0.31$]). This was because in all conditions YA (NN=119ms, FF=112ms, NF=123ms, FN=131ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI (NN=626ms, FF=959ms, NF=792ms, FN=694ms). For condition two and three OA (FF=415ms, NF=180ms) also produced peak anterior deltoid closer to PV than participants with an icSCI. Repeated measures ANOVAs (for each group to determine the main effect of condition) revealed that for participants with an icSCI [$F(3,11)=3.15$, $p>0.05$, $\eta^2=0.46$] and YA [$F(3,13)=0.11$, $p>0.05$, $\eta^2=0.02$] there was no significant main effect of condition. However, for OA there was a significant main effect of condition [$F(3,10)=4.41$, $p<0.05$, $\eta^2=0.57$] as in condition three (NF=180ms) anterior deltoid activity was produced closer to PV than condition one (NN=357ms) and four (FN=374ms).

7.4.2 Biceps Brachii

YA (M=109ms) produced peak biceps brachii activity closer to PV than participants with an icSCI (M=523ms) [$F(2,39)=10.66$, $p<0.001$, $\eta^2=0.35$]. In relation to the start of FAP there was no significant main effect of group [$F(2,38)=1.34$, $p>0.05$, $\eta^2=0.07$] and for both kinematic events the main effects of condition (PV [$F(3,37)=1.25$, $p>0.05$, $\eta^2=0.06$], FAP [$F(3,36)=2.01$, $p>0.05$, $\eta^2=0.14$]) and limb (PV [$F(1,39)=0.22$, $p>0.05$, $\eta^2=0.01$], FAP [$F(1,38)=0.003$, $p>0.05$, $p=0.000$]) did not reach significance.

7.4.3 Extensor Digitorum Superficialis

There was no significant main effect of group for PV [$F(2,39)=2.47$, $p>0.05$, $\eta^2=0.11$], however, for the start of FAP the main effect reached significance [$F(2,39)=4.65$, $p>0.05$, $\eta^2=0.19$]. This was because participants with an icSCI (M=21ms) produced extensor digitorum superficialis (EDS) activity closer to the start of FAP closer than YA (M=-279ms). A significant main effect of condition emerged for PV [$F(3,37)=19.68$, $p<0.001$, $\eta^2=0.62$], but not for FAP [$F(3,37)=1.01$, $p>0.05$, $\eta^2=0.08$], as peak EDS activity was closer to PV in condition one (NN=209ms) than condition two (FF=279ms) three (NF=311ms) and four (FN=386ms), consistent with the earlier MGA formation in condition one. There was also a significant main effect of limb [$F(1,39)=6.50$, $p<0.05$, $\eta^2=0.14$] for PV, but not for FAP [$F(1,39)=0.001$, $p>0.05$, $\eta^2=0.001$], as EDS activity (M=94ms) was closer to PV for the P/LI limb than the NP/MI limb (M=318ms). Additionally, in relation to PV there was a significant condition by group interaction [$F(6,74)=17.29$, $p<0.001$, $\eta^2=0.58$] and a significant limb by group interaction [$F(2,39)=6.64$, $p<0.01$, $\eta^2=0.25$].

Regarding the condition by group interaction one-way ANOVAs (limb collapsed) were performed for each condition to investigate the difference between groups. For all conditions there was a significant main effect of group (condition (NN) [$F(2,43)=5.86$, $p<0.05$, $\eta^2=0.22$], condition two (FF) [$F(2,43)=56.90$, $p<0.05$, $\eta^2=0.73$], condition three (NF) [$F(2,43)=13.48$, $p<0.001$, $\eta^2=0.40$], condition four (FN) [$F(2,43)=5.96$, $p<0.01$, $\eta^2=0.23$]). This was because for all conditions YA (NN=114ms, FF=109ms, NF=60ms, FN=130ms) produced peak EDS activity closer to PV than participants with an icSCI (NN=720ms, FF=1305ms, NF=685ms, FN=657ms). Additionally, for condition two and three OA (FF=338ms, NF=159ms) produced peak EDS activity closer to PV than participants with an icSCI. Repeated measures ANOVAs (to determine the main effect of condition for each group) showed that for YA [$F(3,13)=1.10$, $p>0.05$, $\eta^2=0.20$] and OA [$F(3,11)=3.44$, $p>0.05$, $\eta^2=0.48$] there was no significant main effect of condition. However, for participants with an icSCI there was a significant main effect of condition [$F(3,11)=26.24$, $p<0.001$, $\eta^2=0.88$] as in condition two (FF=1305ms) peak EDS activity was less coupled to PV than condition one (NN=720ms), three (NF=685ms) and four (FN=657ms). This is consistent with the earlier MGA formation for participants with an icSCI compared to the other groups (YA and OA), and when reaching for the near object.

To address the limb by group interaction one-way ANOVAs (condition collapsed) were performed and revealed that for the P/LI [$F(2,43)=3.40$, $p<0.05$, $\eta^2=0.14$] and NP/MI [$F(2,43)=7.9$, $p<0.05$, $\eta^2=0.29$] limb there was a significant difference between groups. This was because YA (P=117ms, NP=89ms) produced peak EDS activity closer to PV than participants with an icSCI (LI=146ms, MI=524ms). Paired t-tests (to test the difference between the limbs for each group) revealed that for YA [$t(15)=1.44$, $p>0.05$] and OA [$t(13)=-0.75$, $p>0.05$] there was no significant difference between the limbs. However, for participants with an icSCI [$t(13)=-2.58$, $p<0.05$] there was a significant difference as the LI (M=-146ms) limb produced peak extensor digitorum superficialis activity closer to PV than the MI (M=524ms) limb.

7.4.4 Triceps Brachii

There was a significant main effect of group for the time of peak triceps brachii activity and both kinematic events (PV [$F(2,39)=17.72$, $p<0.001$, $\eta^2=0.48$], FAP [$F(2,39)=5.64$, $p<0.01$, $\eta^2=0.22$]). This emerged because YA (M=122ms) and OA (M=261ms) produced peak triceps brachii activity closer to PV than participants with an icSCI (M=699ms). In addition, participants with an icSCI (M=-18ms) produced peak triceps brachii activity closer to the start of FAP than YA (M=-261ms). The main effects of condition (PV [$F(3,37)=0.91$, $p>0.05$, $\eta^2=0.07$], FAP [$F(3,37)=0.26$, $p>0.05$, $\eta^2=0.02$]) and limb (PV [$F(1,39)=0.53$, $p>0.05$, $\eta^2=0.01$], FAP [$F(1,39)=0.17$, $p>0.05$, $\eta^2=0.004$]) did not reach significance and no significant interactions emerged.

7.4.5 Agonist-Antagonist muscle activity patterns

As evident in figure 7.6 a significant main effect of group emerged [$F(2,39)=11.44$, $p<0.001$, $\eta^2=0.37$] as the time difference between peak triceps brachii activity and lowest biceps brachii activity was greater for participants with an icSCI (M=502ms) compared to YA (M=36ms) and OA (M=171ms). The main effects of condition [$F(3,37)=1.18$, $p>0.05$, $\eta^2=0.09$] and limb [$F(1,39)=0.18$, $p>0.05$, $\eta^2=0.01$] did not reach significance and no significant interactions occurred.

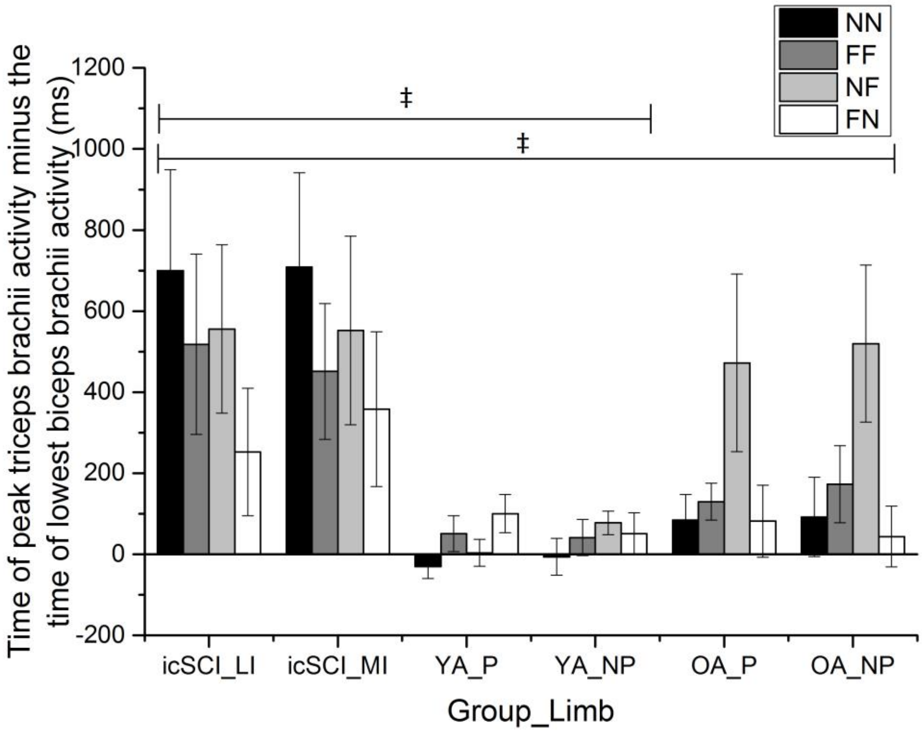

Figure 7.6: Group and limb means (±standard error) for the time difference between the timing of peak triceps brachii activity and lowest biceps brachii activity in NN (black), FF (grey), NF (light grey) and FN (white) conditions. (‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.4.6 Summary of results from experiment one

Participants with an icSCI produced longer (duration) (figure 7.1a), slower (lower peak velocity (figure 7.1b) movements, with an increased proportion of the movement time spent in the deceleration (figure 7.1c) and final adjustment phase (figure 7.1d) than both YA and OA. OA also produced a greater propDT than YA, but this group difference did not continue for propFAP. Consistent with the increase in propDT and propFAP, participants with an icSCI made more adjustments than both YA and OA (approach (figure 7.2a) and final adjustment phase (figure 7.2b).

Movement time and peak velocity were greater in condition two (FF) than the other conditions. For both propDT and propFAP, a condition by limb interaction emerged and subsequent investigations showed that in symmetrical conditions no significant difference emerged between the limbs, but in asymmetrical conditions (condition three and four) the limb moving to the near object had a greater propDT and propFAP than the limb moving to the far object (e.g. P/LI limb greater than the NP/MI limb in condition three (NF)). In the final adjustment phase more adjustments were made by the limb moving to the near object, but for the approach phase there was no significant main effect of condition.

With regards to the grasp phase, results showed that there was no significant main effect of group or condition for MGA. However, subsequent investigations of a limb by group interaction showed that for participants with an icSCI and OA there was a significant difference between limbs, as MGA was greater for the MI limb than LI limb and NP limb than P limb respectively (figure 7.3a). MGA was reached earlier in the movement by participants with an icSCI compared to YA for both limbs and OA for the P/LI limb (figure 7.3b). Consistent with the increased propDT and propFAP, MGA was formed earlier in the movement when moving to the near compared to far object. Transport and grasp phase coupling was weaker for participants with an icSCI compared to YA and OA, although, the group difference was only significant for the

P/LI limb (figure 7.3c). Finally, there was no significant main effect of group for resultant path length (figure 7.4a), but analysis of a condition by limb interaction revealed that in asymmetrical conditions there was a significant difference between limbs, as path length for the limb moving to the near object was shorter than the limb moving the far object as expected. There was no significant main effect of group for path length in the vertical direction or maximum wrist height (figure 7.4b and c).

With regards to interlimb synchrony, participants with an icSCI were less synchronous than both YA and OA at the start, at peak velocity, at the start of the final adjustment phase and at the end of the movement (figure 7.5). A condition by group interaction for the start of the final adjustment phase revealed that for YA and OA the main effect of condition did not reach significance, but for participants with an icSCI the asymmetrical conditions were less synchronous than the symmetrical conditions although these differences did not reach significance.

For all muscles tested (anterior deltoid, biceps brachii, extensor digitorum superficialis and triceps brachii), YA produced peak muscle activity closer to PV than participants with an icSCI. Condition by group interactions showed that OA also produced peak anterior deltoid and extensor digitorum superficialis activity closer to PV than participants with an icSCI in condition two (NN) and three (NF). Participants with an icSCI produced peak anterior deltoid, extensor digitorum superficialis and triceps brachii activity closer to the start of FAP compared to YA. This may have been due to the timing between the peak agonist (triceps brachii) and lowest antagonist (biceps brachii) muscle activity being weaker for participants with an icSCI compared to YA and OA (figure 7.6).

For the extensor digitorum superficialis there was a significant condition by group interaction, exploration of this showed that for participants with an icSCI peak muscle activity was closer to PV in condition one (NN), three (NF) and four (FN) than condition two (FF), consistent with the earlier MGA formation. A condition by limb interaction and subsequent analysis showed that for participants with an icSCI there was a significant difference between limbs, as peak extensor digitorum superficialis activity for the LI limb was closer to PV than the MI limb. Finally, the timing between the peak agonist (triceps brachii) and lowest antagonist (biceps brachii) muscle activity was weaker for participants with an icSCI compared to YA.

Table 7.0: Group and limb means for the timing of peak muscle activity in relation to the timing of kinematic events for each bimanual distance condition (AD=Anterior Deltoid, B=Biceps Brachii, E=Extensor Digitorum Superficialis, T=Triceps Brachii, ST=start of the movement, PV=peak velocity, FAP=start of the final adjustment phase and END=end of the movement). The nearest kinematic event is in **bold**.

Condition one - NN																
	P_AD-ST (ms)	P_AD-PV (ms)	P_AD-FAP (ms)	P_AD-END (ms)	P_B-ST (ms)	P_B-PV (ms)	P_B-FAP (ms)	P_B-END (ms)	P_E-ST (ms)	P_E-PV (ms)	P_E-FAP (ms)	P_E-END (ms)	P_T-ST (ms)	P_T-PV (ms)	P_T-FAP (ms)	P_T-END (ms)
icSCI	960.3	521.2	**-166.1**	-791.1	852.0	412.9	**-274.4**	-744.92	1108.2	669.1	**-18.2**	-612.0	1118.1	679.0	**-8.3**	-585.5
YA	384.9	**98.5**	-302.7	-417.5	362.9	**76.5**	-324.6	-439.52	399.0	**112.6**	-288.6	-403.5	373.1	**86.7**	-314.5	-429.4
OA	674.9	367.9	**-91.6**	-340.9	644.9	337.8	**-121.7**	-371.0	706.0	398.9	**-60.6**	-309.9	599.8	292.8	**-166.8**	-416.0
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1240.9	730.0	**-82.3**	-540.7	932.0	421.1	**-194.1**	-709.3	1280.8	769.9	**154.7**	-469.1	1107.0	596.1	**-19.1**	-617.0
YA	423.1	**139.5**	-266.1	-380.6	405.5	**121.9**	-283.7	-398.1	399.8	**116.2**	-289.4	-403.8	386.8	**103.2**	-302.5	-416.9
OA	657.9	345.8	**-128.1**	-357.7	721.3	409.2	**-64.9**	-294.3	707.3	395.1	**-78.9**	-308.3	600.2	288.0	**-186.0**	-415.4
Condition two - FF																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	1487.0	1012.0	**110.1**	-733.8	1262.4	787.4	**-114.5**	-958.3	1483.0	-2470.6	**106.2**	-737.7	1306.4	831.4	**-70.5**	-914.3
YA	440.8	**132.8**	-299.9	-384.9	413.4	**105.4**	-327.3	-412.3	431.6	**123.5**	-309.1	-394.2	419.8	**111.7**	-320.9	-406.0
OA	711.5	406.0	**-114.1**	-320.7	666.5	361.0	**-159.1**	-365.7	617.8	312.3	**-207.8**	-414.3	652.8	347.3	**-172.8**	-379.4
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1072.6	614.3	**-2.4**	-667.9	1417.9	959.52	**342.9**	-322.6	739.3	**281.0**	-335.7	-1001.2	1206.0	747.6	**131.0**	-534.5
YA	400.4	**90.6**	-339.9	-420.9	429.4	**119.65**	-310.9	-391.9	403.9	**94.2**	-336.4	-417.4	465.2	**155.5**	-275.0	-356.1

OA	750.4	424.9	**-127.7**	-311.8	788.8	463.3	**-89.27**	-273.4	741.3	415.8	**-136.8**	-320.9	674.2	348.6	**-204.0**	-388.0
Condition three - NF																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	1243.8	860.3	**154.4**	-649.8	936.9	553.4	**-152.4**	-956.7	1086.8	703.3	**-2.5**	-806.8	1162.1	778.6	**72.8**	-731.5
YA	460.6	**180.1**	-202.4	-303.5	376.8	**96.41**	-286.1	-387.2	376.6	**96.0**	-286.5	-387.6	395.7	**115.1**	-267.4	-368.5
OA	496.7	**169.4**	-210.7	-264.0	466.6	**139.4**	-240.8	-335.7	512.3	**185.0**	-195.1	-268.3	407.2	**79.9**	-300.2	-313.5
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1276.8	845.4	**-16.4**	-633.3	875.4	444.1	**-417.8**	-1034.7	1203.0	771.7	**-90.1**	-707.1	1266.0	834.7	**-27.2**	-644.1
YA	399.7	**66.0**	-259.5	-348.4	442.4	**108.8**	-216.8	-305.7	356.8	**23.1**	-302.4	-391.4	432.1	**98.5**	-227.1	-316.0
OA	593.7	221.1	**-173.4**	-223.3	558.8	**186.3**	-208.3	-242.1	558.4	**185.9**	-208.7	-225.6	483.5	**111.0**	-283.6	-225.4
Condition four - FN																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	1238.1	609.3	**49.8**	-694.4	1079.8	450.9	**-108.6**	-852.8	1193.1	564.2	**4.8**	-739.4	1123.7	494.8	**-64.7**	-808.9
YA	469.1	**129.8**	-194.0	-242.9	442.6	**103.2**	-220.5	-265.8	476.2	**136.8**	-186.9	-252.0	482.7	**143.3**	-180.5	-254.1
OA	717.4	413.9	**-110.2**	-266.6	686.9	383.4	**-140.7**	-297.1	680.6	377.1	**-147.0**	-303.4	591.4	287.9	**-236.2**	-392.6
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1143.7	779.5	**36.9**	-761.8	1010.6	646.4	**-96.2**	-895.0	1113.7	749.5	**6.9**	-791.9	1134.7	770.5	**27.9**	-770.8
YA	427.3	**131.2**	-227.0	-292.0	438.8	**142.7**	-215.5	-278.6	419.0	**122.9**	-235.3	-294.5	455.4	**159.3**	-198.9	-275.7
OA	695.4	396.5	**-75.6**	-295.4	719.7	420.7	**-51.4**	-271.1	667.1	368.1	**-104.0**	-323.7	582.6	283.6	**-188.4**	-408.2

7.5 Results for experiment two – Kinematic data

7.5.1 Movement time

As figure 7.7a shows participants with an icSCI (M=2182ms) produced movements of a longer duration than YA (M=786ms) and OA (M=1055ms), but the difference between YA and OA did not reach significance ($p>0.05$) [$F(2,41)=20.04$, $p<0.001$, $\eta^2=0.49$]. There was a significant main effect of condition [$F(3,39)=7.13$, $p<0.001$, $\eta^2=0.35$] as MT for condition one (SS=1195ms) was significantly shorter than condition two (LL=1478ms). There was no significant difference between the other conditions ($p>0.05$). The main effect of limb did not reach significance [$F(1,41)=0.09$, $p>0.05$, $\eta^2=0.002$].

A significant condition by group interaction emerged [$F(6,78)=3.36$, $p<0.01$, $\eta^2=0.21$] and subsequent repeated measures ANOVAs for each group (limb collapsed) revealed that there was a significant main effect of condition for all three groups (icSCI $F(3,10)=3.70$, $p<0.05$, $\eta^2=0.53$], YA [$F(3,13)=4.53$, $p<0.05$, $\eta^2=0.51$], OA [$F(3,12)=5.22$, $p<0.05$, $\eta^2=0.57$]. For the participants with an icSCI, MT for condition two (LL=2475ms) was significantly longer than condition one (SS=1784ms). However, for both non-injured control groups MT for condition two (LL; YA=816ms, OA=1142ms) was significantly longer than that of condition four (LS; YA=756ms, OA=1024ms). No other significant differences between conditions emerged for the three groups ($p>0.05$). One-way ANOVAs (performed for each condition) revealed that for all conditions there was a significant main effect of group (SS [$F(2,48)=17.51$, $p<0.001$, $\eta^2=0.43$], LL $F(2,44)=22.57$, $p<0.001$, $\eta^2=0.52$], SL [$F(2,45)=13.48$, $p<0.001$, $\eta^2=0.39$], LS [$F(2,45)=16.01$, $p<0.001$, $\eta^2=0.43$]) as participants with an icSCI (SS=1828ms, LL=2475ms, SL=2223ms, LS=2234ms) produced movements of a longer duration that YA (SS=791ms, LL=816ms, SL=782ms, LS=756ms) and OA (SS=1009ms, LL=1134ms, SL=1041ms, LS=1015ms), with no significant difference between YA and OA for any of the four conditions ($p>0.05$).

7.5.2 Peak velocity

There was a significant main effect of group, which is evident in figure 7.7b, [$F(2,41)=11.24$, $p<0.001$, $\eta^2=0.35$] as participants with an icSCI (M=474mm/s) reached a lower PV than YA (M=712mm/s) and OA (M=614mm/s). There was no significant difference between YA and OA ($p>0.05$). The main effects of condition [$F(3,39)=0.64$, $p>0.05$, $\eta^2=0.05$] and limb [$F(1,41)=0.53$, $p>0.05$, $\eta^2=0.01$] did not reach significance and no significant interactions emerged.

7.5.3 Proportion of movement time spent decelerating

A significant main effect of group [$F(2,41)=30.83$, $p<0.001$, $\eta^2=0.60$] emerged as participants with an icSCI (M=77.74%) spent a longer proportion of the movement time decelerating (propDT) when compared to YA (M=62.52%) and OA (M=70.11%) shown in figure 7.7c. There was also a significant main effect of condition [$F(3,39)=12.01$, $p<0.001$, $\eta^2=0.48$] as propDT was greater in condition two (LL=72.10%) compared to condition one (SS=68.86%) with no significant difference between other conditions ($p>0.05$). The main effect of limb [$F(1,41)=0.12$, $p>0.05$, $\eta^2=0.003$] did not reach significance and no significant interactions emerged.

7.5.4 Proportion of movement time spent in the final adjustment phase

As evident in figure 7.7d there was a significant main effect of group [$F(2,41)=9.17$, $p<0.01$, $\eta^2=0.31$] as participants with an icSCI (M=38.67%) spent a greater proportion of movement time spent in the final adjustment phase than YA (M=13.53%). There was no significant difference between YA and OA or participants with an icSCI and OA ($p>0.05$). A significant main effect of condition also emerged [$F(3,39)=7.31$, $p<0.01$, $\eta^2=0.36$] as propFAP in condition two (LL=29.97%) and condition four (LS=27.39%) was significantly longer than condition one (SS=23.12%). The main effect of limb did not reach significance [$F(1,41)=0.12$, $p>0.05$, $\eta^2=0.003$].

A significant condition by group interaction emerged [$F(6,78)=2.31$, $p<0.05$, $\eta^2=0.15$] and subsequent repeated measures ANOVAs (limb collapsed) were performed for each group revealing that for participants with an icSCI [$F(3,10)=5.17$, $p<0.05$, $\eta^2=0.61$] there was a significant main effect of condition as propFAP for condition one (SS=30.20%) was significantly less than in condition two (LL=43.24%) and four (LS=40.87%). There was no significant main effect of condition for YA [$F(3,13)=0.70$, $p>0.05$, $\eta^2=0.14$] and OA [$F(3,12)=2.53$, $p>0.05$, $\eta^2=0.39$]. One-way ANOVAs (for each condition) revealed that for all four conditions (SS [$F(2,48)=6.47$, $p<0.01$, $\eta^2=0.22$], LL [$F(2,44)=11.37$, $p<0.001$, $\eta^2=0.35$], SL [$F(2,45)=8.41$, $p<0.01$, $\eta^2=0.28$], LS [$F(2,45)=10.81$, $p<0.001$, $\eta^2=0.34$]) there was a significant difference between groups as participants with an icSCI (SS=33.94%, LL=43.24%, SL=41.92%, LS=43.22%) spent a longer proportion of the movement in the final adjustment phase compared to YA (SS=12.90%, LL=15.30%, SL=13.38%, LS=12.55%).

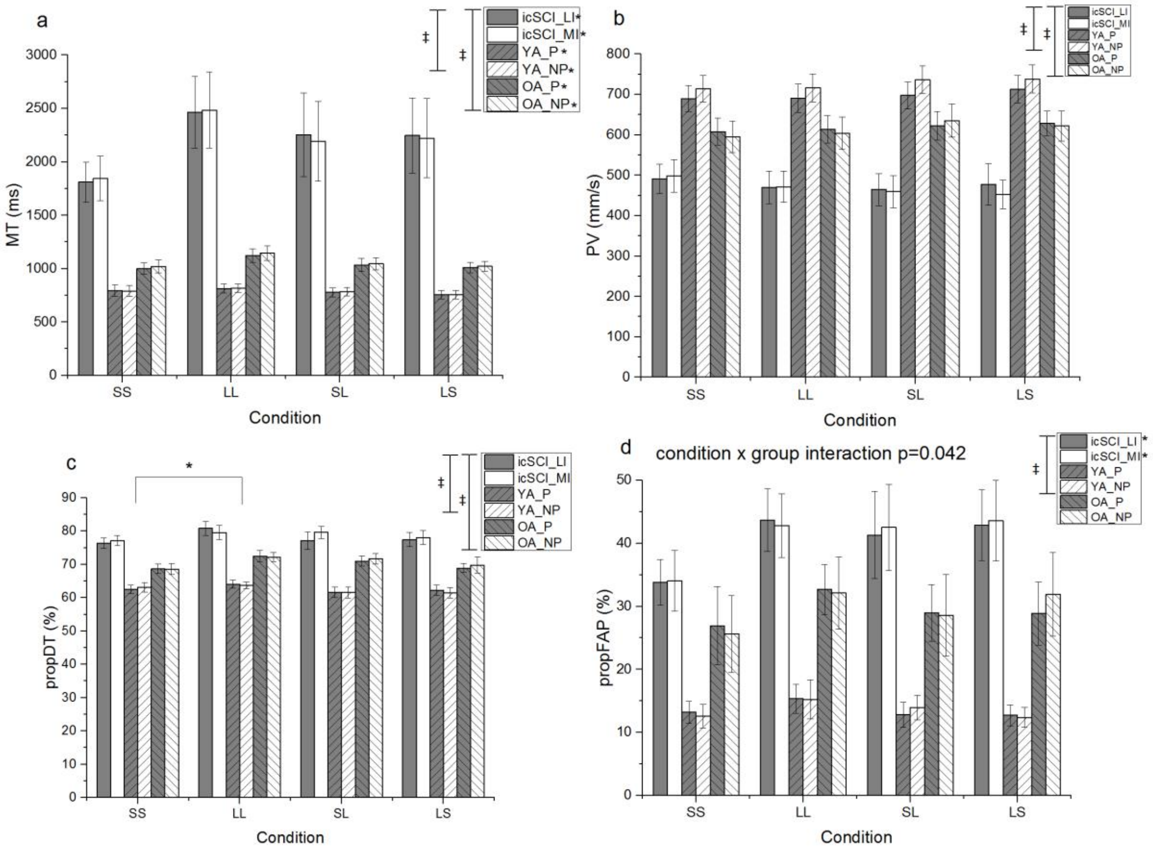

Figure 7.7: Group and limb means (±standard error) for movement time (MT) (a), peak velocity (PV) (b), proportion of movement time spent decelerating (propDT) (c) and proportion of movement time spent in the final adjustment phase (propFAP) (d) in each condition (SS, LL, SL, LS). (* denotes significant difference between conditions and ‡ represents a significant difference between groups), (icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.5.5 Number of adjustments in the approach phase

The main effect of group reached significance (figure 7.8a) [$F(2,41)=28.19$, $p<0.001$, $\eta^2=0.58$] as participants with an icSCI (M=4.25) produced a greater number of adjustments than YA (M=0.55) and OA (M=1.79). There was also a significant difference between YA and OA ($p<0.05$). A significant main effect of condition also emerged [$F(3,39)=5.94$, $p<0.05$, $\eta^2=0.31$] as significantly more adjustments were made in condition two (LL=2.71) compared to condition one (SS=2.01), condition three

(SL=1.97) and condition four (LS=2.09). The main effect of limb did not reach significance [$F(1,41)=1.86$, $p>0.05$, $\eta^2=0.04$].

A significant condition by limb interaction emerged [$F(3,39)=3.247$, $p<0.05$, $\eta^2=0.20$] and subsequent paired t-tests for each condition (group collapsed) showed that for condition one [$t(48)=-1.35$, $p>0.05$], two [$t(44)=-0.62$, $p>0.05$] and four [$t(45)=-0.05$, $p>0.05$] there was no significant difference between limbs. For condition three (SL) there was a significant difference between limbs [$t(45)=-2.16$, $p<0.05$] as the NP/MI limb moving to the large object (M=2.16) made more adjustments than the P/LI limb (M=1.60) moving to the small object. Repeated measures ANOVAs (for each limb) revealed that for the P/LI limb there was a significant main effect of condition [$F(3,41)=4.37$, $p<0.01$, $\eta^2=0.24$] as more adjustments were made in condition two (LL=2.50) compared to condition one (M=1.77) and three (M=1.55). For the NP/MI limb there was also a significant main effect of condition [$F(3,41)=3.69$, $p<0.05$, $\eta^2=0.21$] as more adjustments were made in condition two (LL=2.61) than condition one (SS=2.02), three (SL=2.17) and four (LS=1.93).

7.5.6 Number of adjustments in the final adjustment phase

As evident in figure 7.8b there was a significant main effect of group [$F(2,41)=9.91$, $p<0.001$, $\eta^2=0.33$] as participants with an icSCI (M=13.55) produced significantly more adjustments in the final adjustment phase compared to YA (M=1.37) and OA (M=3.17). The main effect of condition also reached significance [$F(3,39)=8.34$, $p<0.001$, $\eta^2=0.39$] as more adjustments were made for condition two (LL=7.12) compared to condition one (SS=3.92). There was no significant difference between other conditions. The main effect of limb did not reach significance [$F(1,41)=6.53$, $p>0.05$, $\eta^2=0.14$].

A significant limb by group interaction emerged [$F(2,41)=3.53$, $p<0.05$, $\eta^2=0.15$] and subsequent paired t-tests for each group (condition collapsed) revealed that for participants with an icSCI [$t(17)=0.16$, $p>0.05$], YA [$t(15)=0.17$, $p>0.05$] and OA [$t(15)=1.37$, $p>0.05$] there was no significant difference between limbs. One-way ANOVAs (for each limb) showed that for the P/LI limb [$F(2,49)=9.91$, $p<0.001$, $\eta^2=0.30$] and NP/MI limb [$F(2,49)=9.40$, $p<0.001$, $\eta^2=0.29$] there was a significant difference between groups as participants with an icSCI (LI=14.49, MI=14.39) produced more adjustments than YA (P=1.36, NP=1.38) and OA (P=3.29, NP=3.01).

There was also a significant condition by group interaction [$F(6,78)=4.79$, $p<0.001$, $\eta^2=0.27$] and repeated measures ANOVAs for each group (limb collapsed) revealed that for participants with an icSCI [$F(3,10)=4.83$, $p<0.05$, $\eta^2=0.59$] and OA

[F(3,13)=3.93, $p<0.05$, $\eta^2=0.48$] there was a significant main effect of condition, but not for YA [F(3,12)=0.73, $p>0.05$, $\eta^2=0.16$]. For participants with an icSCI condition one (SS=7.59) resulted in less adjustments than condition two (LL=16.08), and this was also true for OA (SS=2.56, LL=3.82). One-way ANOVAs (for each condition) revealed that for condition one [F(2,48)=5.60, $p<0.01$, $\eta^2=0.19$], two [F(2,44)=14.44, $p<0.001$, $\eta^2=0.41$], three [F(2,45)=6.69, $p<0.01$, $\eta^2=0.24$] and four [F(2,45)=10.90, $p<0.001$, $\eta^2=0.34$] there was a significant difference between groups as participants with an icSCI (SS=9.85, LL=16.08, SL=15.84, LS=14.46) produced more adjustments than YA (SS=1.55, LL=1.37, SL=1.38, LS=1.27) and OA (SS=2.56, LL=3.82, SL=3.24, LS=2.81).

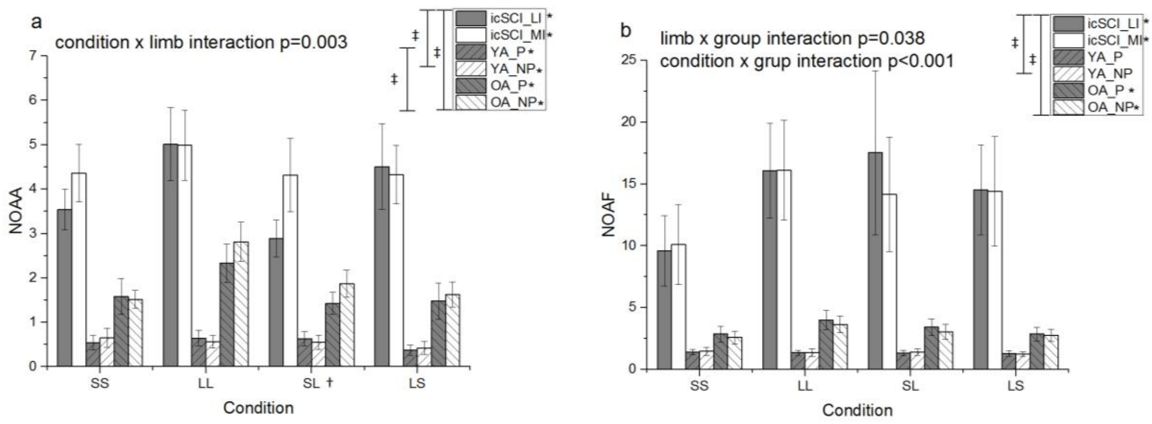

Figure 7.8: Group and limb means (±standard error) for number of adjustments in the approach phase (NOAA) (a) and number of adjustments in the final adjustment phase (NOAF) (b) in each condition (SS, LL, SL, LS). (* denotes a significant difference between conditions and ‡ represents a significant difference between groups),(icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.5.7 Maximum grasp aperture

The main effect of group did not reach significance [F(2,41)=0.81, $p>0.05$, $\eta^2=0.04$], but a significant main effect of condition emerged (figure 7.9a) [F(3,39)=241.09, $p<0.001$, $\eta^2=0.95$] as MGA for condition two (LL=12.3cm) was significantly larger than condition one (SS=9.8cm), three (SL=11.2cm) and four (LS=11.1cm). MGA in condition one (SS) was also significantly smaller than condition three (SL) and four (LS). There was no significant difference between condition three and four ($p>0.05$). The main effect of limb did not reach significance [$F(1,41)=1.89$, $p>0.05$, $\eta^2=0.04$] and no significant interactions emerged.

7.5.8 Time of maximum grasp aperture as a percentage of movement time

As shown in figure 7.9b there was a significant main effect of group [$F(2,41)=11.20$, $p<0.001$, $\eta^2=0.35$] as participants with an icSCI (M=49.05%) reached MGA earlier in the movement compared to YA (M=60.96%). There was no significant difference between participants with an icSCI and OA or YA and OA ($p>0.05$). The main effects of condition [$F(3,39)=0.88$, $p>0.05$, $\eta^2=0.06$] or limb [$F(1,41)=1.55$, $p>0.05$, $\eta^2=0.04$] did not reach significance.

A significant condition by limb interaction emerged [$F(3,39)=10.14$, $p<0.001$, $\eta^2=0.44$] and subsequent paired t-tests (group collapsed) for each condition revealed that for the symmetrical conditions (SS [$t(48)=0.03$, $p>0.05$] and LL [$t(44)=0.69$, $p>0.05$]) there was no significant difference between limbs. For the asymmetrical conditions, (SL [$t(45)=-2.42$, $p<0.05$] and LS [$t(45)=5.06$, $p<0.001$]) the limb reaching towards the small object (P/LI limb in condition three (M=52.82%), NP/MI limb in condition four (M=53.24%)) reached MGA earlier in the movement than the limb reaching for the large object (NP/MI limb in condition three (M=56.35%), P/LI limb in condition four (M=58.84%). Repeated measures ANOVAs (performed on each limb) revealed that for the P/LI limb there was a significant main effect of condition [$F(3,41)=12.87$, $p<0.001$, $\eta^2=0.48$] as MGA was reached earlier in condition three (SL=52.85%) than condition one (SS=56.43%), two (LL=55.85%) and four (LS=58.99%). Additionally, MGA was reached significantly later in condition four than condition one and two. For the NP/MI limb there was no significant main effect of condition [$F(3,41)=2.77$, $p>0.05$, $\eta^2=0.17$].

7.5.9 Transport and grasp coupling

There was a significant main effect of group [$F(2,41)=11.64$, $p<0.001$, $\eta^2=0.36$] as participants with an icSCI (M=329ms) produced less coupled transport and grasp phases that YA (M=57ms) and OA (M=136ms) as shown in figure 7.9c. There was no significant difference between YA and OA. A significant main effect of condition emerged [$F(3,39)=7.69$, $p<0.001$, $\eta^2=0.37$] as the transport and grasp phases in condition two (LL=227ms) were less coupled than condition one (SS=137ms) and condition three (SL=144ms). There was no significant difference for other conditions ($p>0.05$). The main effect of limb did not reach significance [$F(1,41)=0.000$, $p>0.05$,

η^2=0.002], but a significant condition by limb interaction [$F(3,39)=4.32$, $p<0.05$, η^2=0.25] and condition by group interaction emerged [$F(6,78)=3.30$, $p<0.01$, η^2=0.20].

To address the condition by limb interaction subsequent paired t-tests (group collapsed) were performed for each condition and revealed that for condition one [$t(48)=1.24$, $p>0.05$], two [$t(44)=-0.29$, $p>0.05$] and four [$t(45)=-1.50$, $p>0.05$] there was no significant difference between limbs. However, there was a significant difference for condition three [$t(45)=2.154$, $p<0.05$] as the NP/MI limb (M=176.36ms) reaching for the large object produced a less coupled transport and grasp phase than the P/LI limb (M=110.89ms) reaching for the small object. Repeated measures ANOVAs (performed for each limb) revealed that for the P/LI limb there was a significant main effect of condition [$F(3,41)=5.05$, $p<0.01$, η^2=0.27] as the transport and grasp phases were more coupled in condition one (SS=127ms) and condition three (SL=106ms) compared to condition two (LL=219ms) and four (LS=205ms). Therefore when reaching to the small object the transport and grasp phases were more coupled. For the NP/MI limb there was no significant main effect of condition [$F(3,41)=1.68$, $p>0.05$, η^2=0.11].

For the condition by group interaction repeated measures ANOVAs (limb collapsed) performed for each group revealed that for the participants with an icSCI [$F(3,10)=3.67$, $p<0.05$, η^2=0.52] and YA [$F(3,13)=3.53$, $p<0.05$, η^2=0.52] there was a significant main effect of condition but not for OA [$F(3,12)=3.25$, $p>0.05$, η^2=0.45]. For the participants with an icSCI the transport and grasp phases in condition one (SS=257ms) were more coupled than condition two (LL=430ms), and in condition three (SL=235ms) were more coupled than condition two (LL=430ms) and four (LS=393ms). For YA, consistent with participants with an icSCI, the transport and grasp phases in condition one (SS=47ms) were more coupled that condition two (LL=77ms). One-way ANOVAs (for each condition) revealed that for condition one [$F(2,48)=10.15$, $p<0.001$, η^2=0.31], two [$F(2,44)=11.59$, $p<0.001$, η^2=0.43] three [$F(2,45)=5.97$, $p<0.01$, η^2=0.22] and four [$F(2,45)=13.02$, $p<0.001$, η^2=0.38] there was a significant difference between groups. This was because participants with an icSCI (SS=317.64ms, LL=430.13ms, SL=246.48ms, LS=408.57ms) produced less coupled transport and grasp phases than YA (SS=46.99ms, LL=77.38ms, SL=50.19ms, LS=55.17ms) and OA (SS=105.86ms, LL=175.18ms, LS=187.36ms). There was no significant difference between participants with an icSCI and OA for condition three ($p>0.05$).

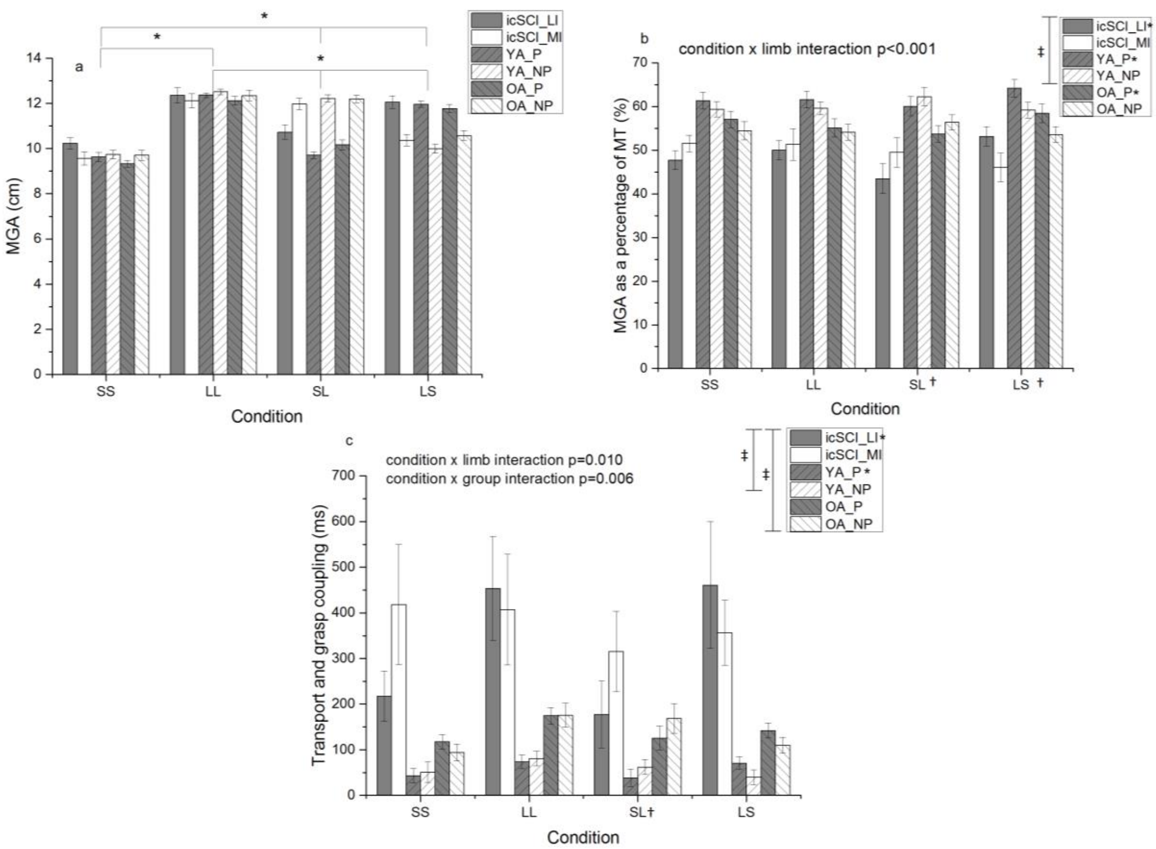

Figure 7.9: Group and limb means (±standard error) for maximum grasp aperture (MGA) (a), time of maximum grasp aperture as a percentage of movement time (MGA as a percentage of MT) (b) and transport and grasp phase coupling (c) in each condition (SS, LL, SL, LS). (* denotes significant difference between conditions, † reflects significant difference between the limbs and ‡ represents a significant difference between groups), (icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.5.10 Path length

A significant main effect of group emerged [$F(2,41)=5.68$, $p<0.01$, $\eta^2=0.22$] as participants with an icSCI produced significantly longer resultant PL (M=31.3cm) than YA (M=25cm) and OA (M=24.7cm) (figure 7.10a). There was also a significant main effect of condition [$F(3,39)=3.66$, $p<0.05$, $\eta^2=0.22$] as resultant PL for condition two

(LL=28.1cm) was significantly longer than that of condition one (SS=26.6cm). The main effect of limb did not reach significance [$F(1,41)=0.58$, $p>0.05$, $\eta^2=0.01$].

A significant condition by limb interaction emerged [$F(3,39)=3.44$, $p<0.05$, $\eta^2=0.21$] and subsequent paired t-tests (group collapsed) revealed that for all four conditions there was no significant difference between limbs ([condition one [$t(48)=0.07$, $p>0.05$], condition two [$t(44)=-1.54$, $p>0.05$], condition three [$t(45)==0.62$, $p>0.05$, condition four [$t(45)=0.35$, $p>0.05$]). Repeated measures ANOVAs (performed on each limb) revealed that for the P/LI limb there was no significant main effect of condition [$F(3,41)=1.25$, $p>0.05$, $\eta^2=0.08$]. However, for the NP/MI limb there was a significant main effect of condition [$F(3,41)=3.59$, $p<0.05$, $\eta^2=0.21$] as PL for condition two (LL=28.3cm) was significantly greater than condition one (SS=26.3cm) and four (LS=26.5cm).

With regards to path length in the vertical direction (z) (figure 7.10b) there was no significant main effect of group [$F(2,41)=1.77$, $p>0.05$, $\eta^2=0.08$], condition [$F(3,39)=2.10$, $p>0.05$, $\eta^2=0.14$] or limb [$F(1,41)=0.70$, $p>0.05$, $\eta^2=0.02$] and no significant interactions emerged. Additionally, there was no significant main effect of group [$F(2,41)=3.33$, $p>0.05$, $\eta^2=0.14$], condition [$F(3,39)=1.79$, $p>0.05$, $\eta^2=0.12$] or limb [$F(1,41)=1.48$, $p>0.05$, $\eta^2=0.04$] for maximum wrist height and no significant interactions emerged (figure 7.10c).

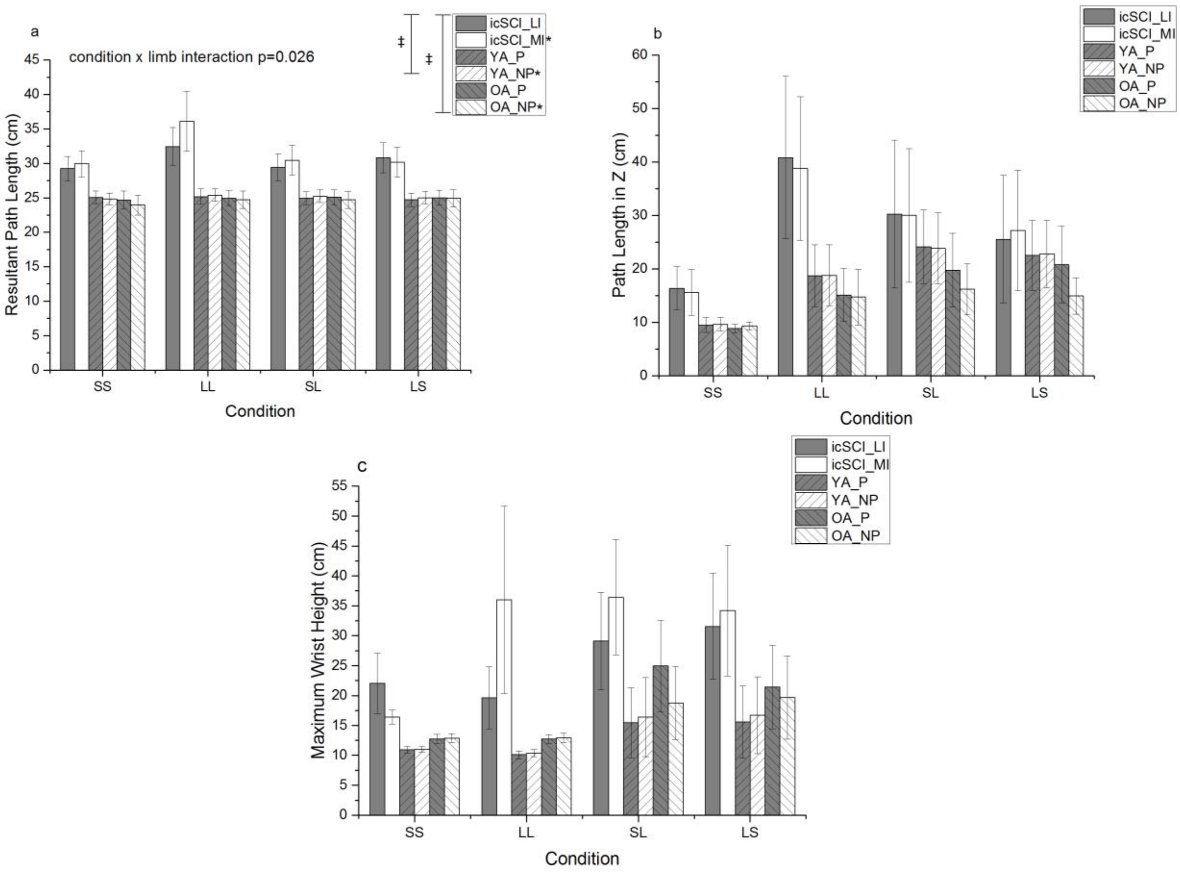

Figure 7.10: Group and limb means (±standard error) for resultant path length (a), path length in the vertical direction (z) (b) and maximum wrist height (c) in each condition (SS, LL, SL, LS). (* denotes significant difference between conditions and ‡ represents a significant difference between groups), (icSCI_LI = grey, icSCI_MI = white, YA_P = grey and right pattern, YA_NP = white and right pattern, OA_P = grey and left pattern, OA_NP = white and left pattern, icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.5.11 Interlimb synchrony

At the start [$F(2,41)=5.32$, $p<0.01$, $\eta^2=0.21$], peak velocity [$F(2,41)=11.27$, $p<0.001$, $\eta^2=0.36$], start of the final adjustment phase [$F(2,41)=19.04$, $p<0.001$, $\eta^2=0.48$] and end of the movement there was a significant main effect of group [$F(2,41)=19.04$, $p<0.01$, $\eta^2=0.20$]. This was because participants with an icSCI (START=57ms, PV=98ms, FAP=164ms, END=135ms) were less synchronous than YA (START=19ms, PV=20ms, FAP=47ms, END=22ms) throughout the entire movement and less synchronous than OA at peak velocity (M=34ms), start of final adjustment phase (M=79ms) and end of the movement (M=25ms), as shown in figure 7.11a-d. Synchrony between the limbs improved for all groups between the start of the final adjustment phase and end of the movement (see figure 7.11c and 7.11d). At the start [$F(3,39)=2.20$, $p>0.05$, $\eta^2=0.14$], peak velocity [$F(3,39)=1.01$, $p>0.05$, $\eta^2=0.07$] and start of the final adjustment phase [$F(3,39)=1.60$, $p>0.05$, $\eta^2=0.11$] the main effect of condition did not reach significance but at the end of the movement significance emerged [$F(3,39)=2.94$, $p<0.05$, $\eta^2=0.19$]. This was because condition three (SL=96ms) was significantly less synchronous than condition one (SS=36ms). No significant interactions emerged.

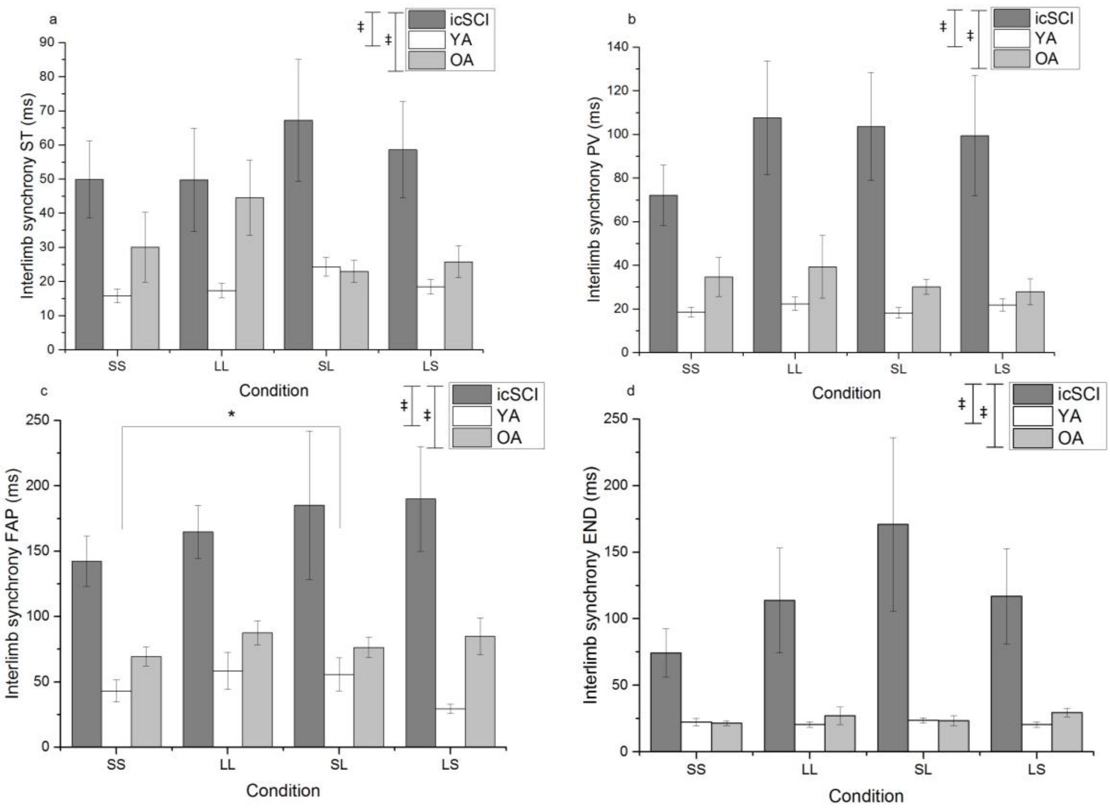

Figure 7.11: Group means (±standard error) for interlimb synchrony at the start of the movement (ST) (a), at peak velocity (PV) (b), at the start of the final adjustment phase (FAP) (c), at the end of the movement (END) (d) in each condition (SS, LL, SL, LS). (* denotes significant difference between conditions and ‡ represents a significant difference between groups), (icSCI = dark grey, YA_P = white, OA = light grey; error bars are standard error (icSCI = incomplete cervical Spinal Cord Injury, YA = non-injured younger adults, OA = non-injured older adults).

7.6 EMG analysis

The timing of peak muscle activity occurred between peak velocity and the start of the final adjustment phase for all groups (as shown in table 7.1), and therefore these were the focus of subsequent statistical analyses.

7.6.1 Anterior Deltoid

For both peak velocity [$F(2,37)=27.89$, $p<0.001$, $\eta^2=0.60$] and the start of the final adjustment phase [$F(2,37)=16.73$, $p<0.001$, $\eta^2=0.48$] there was a significant main effect of group as YA (M=116ms) produced peak anterior deltoid activity closer to peak velocity than participants with an icSCI (M=842ms) and OA (M=400ms). OA also produced peak anterior deltoid closer to PV than participants with an icSCI. However, participants with an icSCI (M=163ms) and OA (M=-82ms) produced peak anterior deltoid activity closer to the start of the final adjustment phase when compared to YA (M=-272ms). A significant main effect of condition also emerged for peak velocity [$F(3,35)=6.51$, $p<0.01$, $\eta^2=0.36$] and the final adjustment phase [$F(3,35)=5.52$, $p<0.01$, $\eta^2=0.32$] as peak anterior deltoid activity was closer to PV in condition one (SS=309ms) compared to condition two (LL=532ms) and three (SL=503ms). Additionally, peak anterior deltoid activity was closer to the start of FAP in condition three (SL=13ms) compared to condition one (SS=-190ms). The main effect of limb did not reach significance in relation to peak velocity [$F(1,37)=1.88$, $p>0.05$, $\eta^2=0.05$] or the final adjustment phase [$F(1,37)=0.39$, $p>0.05$, $\eta^2=0.01$].

A significant condition by group interaction emerged in relation to peak velocity [$F(6,70)=4.12$, $p<0.01$, $\eta^2=0.26$] and the final adjustment phase [$F(6,70)=3.69$, $p<0.01$, $\eta^2=0.24$]. To investigate these interactions one-way ANOVAs (limb collapsed) were performed for each condition and showed that in relation to peak velocity, for condition one (SS) [$F(2,42)=5.05$, $p<0.05$, $\eta^2=0.20$], condition two (LL) [$F(2,39)=27.17$, $p<0.001$, $\eta^2=0.60$], condition three (SL) [$F(2,39)=10.08$, $p<0.001$, $\eta^2=0.35$] and condition four (LS) [$F(2,39)=41.81$, $p<0.001$, $\eta^2=0.69$] there was a significant difference between groups. This was because YA (SS=119ms, LL=97ms, SL=129ms, LS=122ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI (SS=626ms, LL=1043ms, SL=963ms, LS=909ms) in all four conditions. Additionally, in condition two, three and four OA (LL=456ms, SL=417ms, LS=370ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI. In condition two and four YA also produced peak anterior deltoid activity closer to PV than OA.

For the final adjustment phase one-way ANOVAs (for each condition) showed that for condition two [$F(2,39)=10.86$, $p<0.001$, $\eta^2=0.37$], three [$F(2,39)=7.08$, $p<0.01$, $\eta^2=0.28$]

and four [$F(2,39)=11.68$, $p<0.001$, $\eta^2=0.39$] there was a significant difference between groups. This was because participants with an icSCI (LL=225ms SL=362ms, LS=229ms) produced peak anterior deltoid activity after the start of the final adjustment phase whereas YA produced peak anterior deltoid activity before the start of the final adjustment phase (closer to PV) (SS=-301ms, SL=-253ms, LS=-259ms). Additionally, in condition three and four the OA (LS=-70ms, LS=-107ms) also produced peak anterior deltoid activity before the start of the final adjustment phase, resulting in a significant difference between OA and participants with an icSCI. The group difference did not reach significance for condition one [$F(2,42)=1.83$, $p>0.05$, $\eta^2=0.08$].

Repeated measures ANOVAs (performed for each group) revealed that in relation to peak velocity and the final adjustment phase the main effect of condition did not reach significance for YA (PV [$F(3,12)=0.34$, $p>0.05$, $\eta^2=0.08$], FAP [$F(3,12)=0.91$, $p>0.05$, $\eta^2=0.18$]) and OA (PV [$F(3,10)=1.15$, $p>0.05$, $\eta^2=0.26$], FAP [$F(3,10)=0.75$, $p>0.05$, $\eta^2=0.18$]), but for participants with an icSCI significance was reached (PV [$F(3,9)=5.81$, $p<0.05$, $\eta^2=0.66$], FAP [$F(3,9)=4.36$, $p<0.05$, $\eta^2=0.59$]). This was because for participants with an icSCI peak anterior deltoid activity was closer to PV for condition one (SS=452ms) compared to condition three (SL=963ms), whereas it was before the start of the final adjustment phase in condition one (SS=-184ms) and after in condition three (SL=362ms).

7.6.2 Biceps Brachii

The main effect of group reached significance for peak velocity [$F(2,37)=13.64$, $p<0.001$, $\eta^2=0.42$] and the start of the final adjustment phase [$F(2,37)=6.75$, $p<0.01$, $\eta^2=0.27$]. This was because YA (M=112ms) produced peak biceps brachii activity closer to peak velocity compared to participants with an icSCI (M=696ms) and OA (M=429ms). On the other hand, participants with an icSCI (M=16ms) and OA (M=-58ms) produced peak biceps brachii activity closer to the start of the final adjustment phase than YA (M=-276ms). A significant main effect of condition also emerged in relation to peak velocity [$F(3,35)=9.20$, $p<0.001$, $\eta^2=0.44$] and the final adjustment phase [$F(3,35)=5.03$, $p<0.01$, $\eta^2=0.30$] as peak biceps brachii activity was closer to peak velocity in condition one (SS=256ms) compared to condition two (LL=505ms) and four (LS=417ms), and closer to the start of the final adjustment phase in condition three (SL=-20ms) and four (LS=-95ms) compared to condition one (SS=-244ms). The main effect of limb did not reach significance in relation to peak velocity [$F(1,37)=1.58$, $p>0.05$, $\eta^2=0.04$] of the start of the final adjustment phase [$F(1,37)=0.70$, $p=0.41$, $\eta^2=0.02$].

A condition by group interaction emerged [$F(6,70)=4.58$, $p<0.01$, $\eta^2=0.28$] for peak velocity and the final adjustment phase [$F(6,70)=2.85$, $p<0.05$, $\eta^2=0.20$]. Subsequent one-way ANOVAs (limb collapsed) were performed for each condition to explore this and showed that for condition one [$F(2,42)=3.90$, $p<0.05$, $\eta^2=0.16$], two [$F(2,39)=17.12$, $p<0.001$, $\eta^2=0.48$], three [$F(2,39)=6.76$, $p<0.01$, $\eta^2=0.22$] and four [$F(2,39)=8.71$, $p<0.01$, $\eta^2=0.32$] there was significant difference between groups as YA (SS=99ms, LL=87ms, SL=99ms, LS=166ms) produced peak biceps brachii activity closer to peak velocity than participants with an icSCI (SS=417ms, LL=918ms, SL=855ms, LS=710ms). Additionally, in condition two (LL) OA (M=509ms) produced peak biceps brachii activity closer to peak velocity than participants with an icSCI, and YA produced peak biceps brachii activity closer to peak velocity than OA.

In relation to the final adjustment phase one-way ANOVAs were also performed and showed a significant group difference emerged for condition two [$F(2,39)=6.99$, $p<0.05$, $\eta^2=0.27$] and three [$F(2,39)=4.60$, $p<0.05$, $\eta^2=0.20$] as participants with an icSCI (LL=120ms, SL=254ms) produced peak biceps brachii activity after the start of the final adjustment phase, whereas YA (LL=-310ms, SL=-284ms) produced peak biceps brachii activity before the start of the final adjustment phase (closer to peak velocity). Additionally, in condition two OA (M=-83ms) produced peak biceps brachii activity closer to the start of the final adjustment phase when compared to YA. For condition one [$F(2,42)=1.59$, $p>0.05$, $\eta^2=0.07$] and four [$F(2,39)=2.68$, $p>0.05$, $\eta^2=0.13$] there was no significant difference between groups.

Repeated measures ANOVAs (for each group) revealed that in relation to peak velocity the main effect of condition did not reach significance for YA [$F(3,12)=1.57$, $p>0.05$, $\eta^2=0.28$] or OA [$F(3,10)=3.28$, $p>0.05$, $\eta^2=0.50$], but reached significance for participants with an icSCI [$F(3,9)=7.00$, $p<0.05$, $\eta^2=0.70$]. This significance emerged as peak biceps brachii activity was closer to peak velocity in condition one (SS=297ms) compared to condition four (LS=710ms). In relation to the final adjustment phase repeated measures ANOVAS (for each group) revealed that the main effect of condition did not reach significance for any of the groups (icSCI [$F(3,9)=3.37$, $p>0.05$, $\eta^2=0.53$], YA [$F(3,12)=1.63$, $p>0.05$, $\eta^2=0.29$], OA [$F(3,10)=1.64$, $p>0.05$, $\eta^2=0.33$].

7.6.3 Extensor Digitorum Superficialis

A significant main effect of group emerged in relation to peak velocity [$F(2,37)=20.19$, $p<0.001$, $\eta^2=0.52$] and final adjustment phase [$F(2,37)=12.07$, $p<0.001$, $\eta^2=0.40$] as YA (M=129ms) produced peak extensor digitorum superficialis (EDS) activity closer to peak velocity than participants with an icSCI (M=860ms) and OA (M=425ms). OA also produced EDS activity closer to PV than participants with an icSCI. In relation to the final adjustment phase participants with an icSCI (M=181ms) produced peak EDS activity after the start of final adjustment phase, whereas, YA produced peak extensor activity before the start of FAP (closer to PV) (M=-259ms). Additionally, OA (M=-62ms) produced peak EDS activity closer to the start of the final adjustment phase than participants with an icSCI. The main effect of condition reached significance for peak velocity [$F(3,35)=5.39$, $p<0.01$, $\eta^2=0.32$] and the final adjustment phase [$F(3,35)=4.28$, $p<0.05$, $\eta^2=0.27$]. This was because peak EDS activity occurred closer to peak velocity in condition one (M=354ms) than condition three (M=530ms), and closer to the start of the final adjustment phase than peak velocity in condition three (M=40ms) than condition one (M=145ms). The main effect of limb did not reach significance for peak velocity [$F(1,37)=3.36$, $p>0.05$, $\eta^2=0.08$] or the start of the final adjustment phase [$F(1,37)=1.99$, $p>0.05$, $\eta^2=0.05$].

A significant condition by group interaction emerged for timing of peak EDS activity in relation to peak velocity [$F(6,70)=3.86$, $p<0.01$, $\eta^2=0.25$] and start of final adjustment time [$F(6,70)=3.17$, $p<0.01$, $\eta^2=0.21$]. To explore this further one-way ANOVAs were performed for each condition (limb collapsed) and showed that in relation to peak velocity there was a significant difference between groups for all four conditions (SS [$F(2,42)=5.79$, $p<0.01$, $\eta^2=0.223$], LL [$F(2,40)=31.32$, $p<0.001$, $\eta^2=0.62$], SL [$F(2,40)=7.78$, $p<0.01$, $\eta^2=0.29$], LS [$F(2,40)=27.26$, $p<0.001$, $\eta^2=0.59$]) as YA (SS=114ms, LL=93ms, SL=129ms, LS=161ms) produced peak EDS activity closer to peak velocity than participants with an icSCI (SS=720ms, LL=942ms, SL=1054ms, LS=885ms). Additionally, for condition two, three and four, OA (LL=509ms, SL=398ms, LS=394ms) produced peak EDS activity closer to peak velocity than participants with an icSCI.

Regarding the final adjustment phase one-way ANOVAs (for each condition) showed that for condition two [$F(2,40)=8.41$, $p<0.01$, $\eta^2=0.31$], three [$F(2,40)=5.55$, $p<0.01$, $\eta^2=0.23$] and four [$F(2,40)=7.62$, $p<0.01$, $\eta^2=0.29$] there was a significant difference between groups as participants with an icSCI (LL=144ms, SL=454ms, LS=205ms) produced peak EDS activity after the start of the final adjustment phase, whereas YA (LL=-279ms, SL=-230ms, LS=-196ms) produced peak EDS activity before (closer to PV). This also held true for the OA (M=-83ms) in condition four resulting in a significant group difference to participants with an icSCI. Additionally, in condition two OA (M=-8ms) produced peak EDS activity closer to the start of the final adjustment phase that YA. For condition one there was no significant difference between groups [$F(2,42)=2.58$, $p>0.05$, $\eta^2=0.11$].

Repeated measures ANOVAs (performed for each group) for peak velocity (icSCI [F(3,9)=1.17, p>0.05, η^2=0.13], YA [F(3,13)=0.86, p>0.05, η^2=0.17], OA [F(3,10)=1.81, p>0.05, η^2=0.35]) and the start of the final adjustment phase (icSCI [F(3,9)=3.32, p>0.05, η^2=0.53], YA [F(3,13)=1.92, p>0.05, η^2=0.31], OA [F(3,10)=0.42, p>0.05, η^2=0.11]) showed that the main effect of condition did not reach significance for any of the three groups.

7.6.4 Triceps Brachii

There was a significant main effect of group in relation to peak velocity [F(2,37)=18.63, p<0.001, η^2=0.50] and the final adjustment phase [F(2,37)=10.22, p<0.001, η^2=0.36] as YA (M=130ms) and OA (M=340ms) produced peak triceps brachii activity closer to peak velocity than participants with an icSCI (M=808ms). In agreement with this, participants with an icSCI (M=129ms) produced peak triceps brachii activity closer to and after the start of the final adjustment phase compared to YA (M=-258ms) and OA (M=-147ms). A significant main effect of condition also arose (PV [F(3,35)=7.85, p<0.001, η^2=0.40], FAP [F(3,35)=4.15, p<0.05, η^2=0.26]) as peak triceps brachii activity was closer to peak velocity in condition one (SS=276ms) compared to condition two (LL=516ms), three (SL=480ms) and four (LS=433ms), and closer the start of the final adjustment phase in condition three (SL=-10ms) compared to condition one (SS=-223ms). The main effect of limb did not reach significance (PV [F(1,37)=1.46, p>0.05, η^2=0.04], FAP [F(1,37)=0.73, p>0.05, η^2=0.02]).

A significant condition by group interaction emerged in relation to peak velocity [F(6,70)=3.60, p<0.001, η^2=0.24] and subsequent repeated measures ANOVAs (limb collapsed) for each group revealed that for YA [F(3,12)=1.57, p=>0.05, η^2=0.28] and OA [F(3,10)=2.71, p>0.05, η^2=0.45] there was no significant main effect of condition, but for participants with an icSCI significance was reached [F(3,9)=5.41, p<0.05, η^2=0.64] as peak triceps brachii activity was closer to PV for condition one (SS=446ms) compared to condition two (LL=1036ms).

One-way ANOVAs (for each condition) revealed that for each of the four conditions there was a significant difference between groups (SS [F(2,42)=5.60, p<0.01, η^2=0.22], LL [F(2,39)=20.26, p=<0.001, η^2=0.52], SL [F(2,39)=7.57, p<0.01, η^2=0.29], LS [F(2,39)=12.77, p<0.001, η^2=0.40]). This was because YA (SS=95ms, LL=109ms, SL=149ms, LS=171ms) produced peak triceps brachii activity closer to peak velocity than participants with an icSCI (SS=638ms, LL=1036ms, SL=916ms, LS=835ms) in all four conditions. Additionally, in condition two, three and four OA (LL=483ms, SL=373ms, LS=294ms) also produced peak triceps brachii activity closer to peak velocity than participants with an icSCI.

7.6.5 Agonist-Antagonist muscle activity patterns

As shown in figure 7.12 the main effect of group was significant [$F(2,37)=4.92$, $p<0.05$, $\eta^2=0.21$] as YA (M=4ms) and OA (M=127ms) produced peak triceps brachii activity and lowest biceps brachii activity at a closer time point than participants with an icSCI (M=416ms). The main effect of condition did not reach significance [$F(3,35)=0.86$, $p>0.05$, $\eta^2=0.07$], however, the main effect of limb reached significance [$F(1,37)=5.65$, $p<0.05$, $\eta^2=0.13$] as peak triceps brachii and lowest biceps brachii timing was closer for the P/LI limb (M=131ms) than the NP/MI limb (M=229ms). No significant interactions emerged.

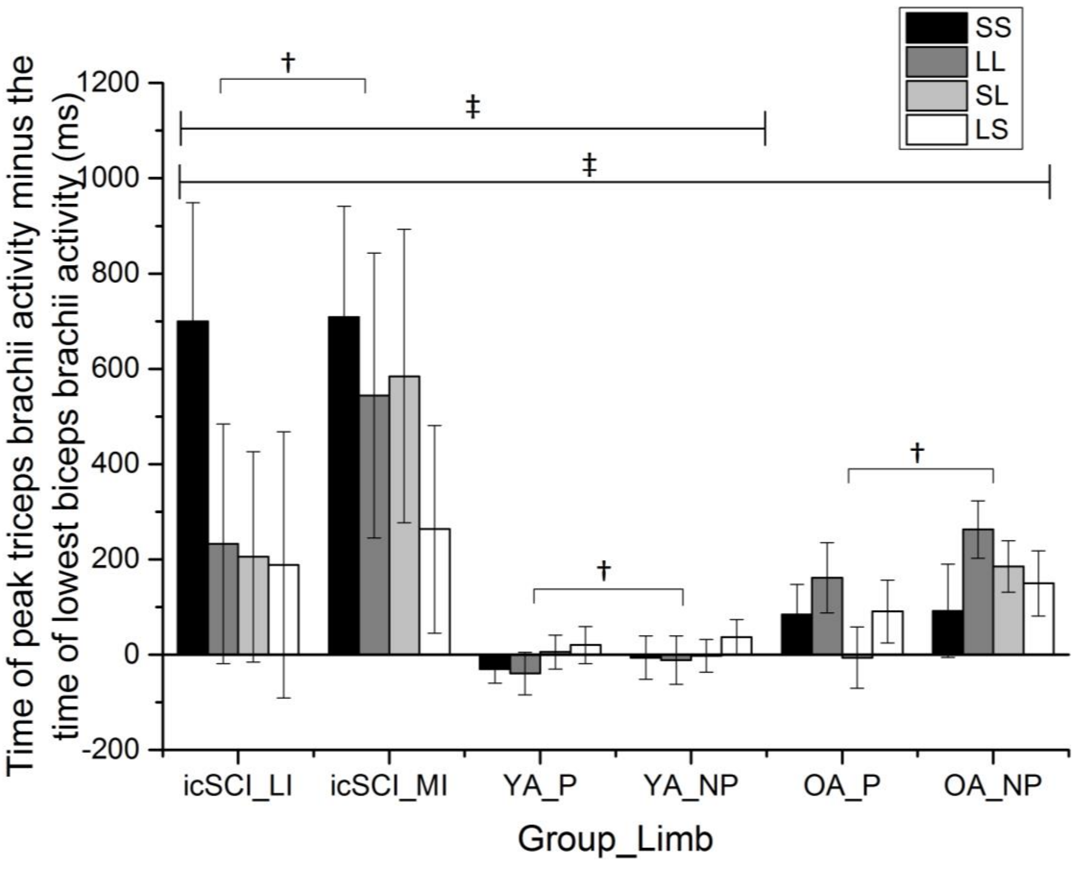

Figure 7.12: Group and limb means (±standard error) for the time difference between the timing of peak triceps brachii activity and lowest biceps brachii activity in SS (black), LL (grey), SL (light grey) and LS (white) conditions. († reflects significant difference between the limbs and ‡ represents a significant difference between

groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

7.6.6 Summary of results from experiment two

Participants with an icSCI produced movements of a longer duration (figure 7.7a), lower peak velocity (figure 7.7b) and spent a longer proportion of movement time in the deceleration phase (figure 7.7c) when compared to YA and OA. They also spent a greater proportion of the movement in the final adjustment phase compared to YA (figure 7.7d). The movements were also less smooth for participants with an icSCI compared to YA and OA (in both the approach (figure 7.8a) and final adjustment phase (figure 7.8b)).

In terms of object size, the results showed that movement time and propDT were greatest in condition two (LL) compared to condition one (SS). However, for propFAP the main effect of condition was only significant for participants with an icSCI, as condition two (LL) and four (LS) resulted in a greater propFAP than condition one (SS). The number of adjustments made were also greater in condition two (LL) for both the approach phase (for both limbs and all participants) and final adjustment phase. However, for the number of adjustments in the final adjustment phase only reached significance for participants with an icSCI and OA, but not YA.

With regards to the grasp phase, the results showed that all groups scaled their MGA to object size (e.g. MGA in condition two greater than the other conditions) (figure 7.9a). However, participants with an icSCI formed their MGA earlier in the movement than YA (figure 7.9b), and produced less coupled transport and grasp phases than YA and OA (figure 7.9c). A condition by limb interaction and subsequent investigations showed that in asymmetrical conditions MGA was formed earlier when reaching to the small compared to large object (e.g. earlier for the P/LI limb than NP/MI limb in condition three (SL)). The earlier MGA formation resulted in the greater coupling between transport and grasp phases when reaching to the small (SS and SL) compared to large object (LL and LS), although this was only significant for the P/LI (revealed by a condition by limb interaction). Further analysis of a condition by group interaction revealed that for participants with an icSCI (SS>LL, SL>LL and LS) and YA (SS>LL) the transport and grasp phases were more coupled when reaching to the small compared to large object, but for OA the main effect of condition was not significant. Finally, participants with an icSCI produced movements with a greater resultant path length when compared to YA and OA (figure 7.10a). Additionally, path length was greater in condition two (LL) than condition one (SS) and four (LS) for the NP/MI limb, but the main effect of condition did not reach significance for the P/LI limb (condition by limb interaction).There was no significant main effect of group, condition or limb for path length in the vertical direction (z) (figure 7.10b) or maximum wrist height (figure 7.10c).

Interlimb synchrony was weaker for participants with an icSCI compared to YA and OA for all kinematic parameters (start, peak velocity, start of final adjustment phase and end of the movement) (figure 7.11). The main effect of condition reached significance at the end of the movement as the limbs were less synchronous in condition three (SL) than condition one (SS).

For all muscles tested (anterior deltoid, biceps brachii, extensor digitorum superficialis and triceps brachii), YA produced peak muscle activity closer to the time of PV than participants with an icSCI. Condition by group interactions showed that OA also produced peak muscle activity (anterior deltoid, biceps brachii, extensor digitorum superficialis, triceps brachii) closer to PV than participants with an icSCI in condition two (LL), three (SL) and four (LS). YA produced peak muscle activity closer to PV than OA in condition two (LL) for the biceps brachii and anterior deltoid, and condition four (LS) for the anterior deltoid. In relation to the start of FAP, participants with an icSCI produced peak anterior deltoid, biceps brachii, extensor digitorum superficialis and triceps brachii muscle activity closer to the start of FAP than YA. In addition, participants with an icSCI produced peak muscle activity after the start of FAP (extensor digitorum superficialis, biceps brachii, anterior deltoid). This later muscle activity may have occurred as timing between the peak agonist (triceps brachii) and lowest antagonist (biceps brachii) muscle activity was weaker for participants with an icSCI compared to YA and OA.

Condition by group interactions showed that for participants with an icSCI peak anterior deltoid activity was closer to PV in condition one (SS) and closer to the start of FAP in condition three (SL). For the biceps brachii peak muscle activity occurred closer to the start of FAP in condition one (SS) than condition four (LS). Peak triceps brachii activity was closer to PV in condition one (SS) than condition two (LL), three (SL) and four (LS), but closer to the start of FAP in condition three (SL) than condition one (SS).

Table 7.1: Group and limb means for the timing of peak muscle activity in relation to the timing of kinematic events for each bimanual size condition (AD=Anterior Deltoid, B=Biceps Brachii, E=Extensor Digitorum Superficialis, T=Triceps Brachii, ST=start of the movement, PV=peak velocity, FAP=start of the final adjustment phase and END=end of the movement). The nearest kinematic event is in **bold**.

Condition one - SS																
	P_AD-ST (ms)	P_AD-PV (ms)	P_AD-FAP (ms)	P_AD-END (ms)	P_B-ST (ms)	P_B-PV (ms)	P_B-FAP (ms)	P_B-END (ms)	P_E-ST (ms)	P_E-PV (ms)	P_E-FAP (ms)	P_E-END (ms)	P_T-ST (ms)	P_T-PV (ms)	P_T-FAP (ms)	P_T-END (ms)
icSCI	960.3	521.2	**-166.1**	-791.1	852.0	412.9	**-274.4**	-744.9	1108.2	669.1	**-18.2**	-612.0	1118.1	679.0	**-8.3**	-585.5
YA	384.9	**98.5**	-302.7	-417.5	362.9	**76.5**	-324.6	-439.5	399.0	**112.6**	-288.6	-403.5	373.1	**86.7**	-314.5	-429.4
OA	674.9	367.9	**-91.6**	-340.9	644.9	337.8	**-121.7**	-371.0	706.0	398.9	**-60.6**	-309.9	599.8	292.8	**-166.8**	-416.1
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1240.94	730.0	**-82.3**	-540.7	932.0	421.1	**-194.1**	-709.3	1280.8	769.9	**154.7**	-469.1	1107.0	596.1	**-19.1**	-617.0
YA	423.08	**139.5**	-266.1	-380.6	405.5	**121.9**	-283.7	-398.1	399.8	**116.2**	-289.4	-403.8	386.8	**103.2**	-302.5	-416.9
OA	657.89	345.8	**-128.3**	-357.7	721.3	409.2	**-64.9**	-294.3	707.3	395.1	**-78.9**	-308.3	600.2	288.0	**-186.0**	-415.4
Condition two - LL																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	1445.5	1031.8	**229.4**	-1090.5	1320.0	906.3	**103.8**	-1216.1	1270.0	856.3	**53.9**	-1266.0	1404.9	991.2	**188.7**	-1131.2
YA	399.9	**122.6**	-291.8	-423.3	338.5	**61.2**	-353.2	-484.7	379.0	**101.7**	-312.7	-444.2	379.9	**102.6**	-311.8	-443.3
OA	742.0	435.4	**-26.2**	-382.8	769.8	474.9	**-28.4**	-385.0	761.5	466.5	**-36.8**	-393.4	658.1	363.2	**-140.1**	-496.7
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1494.2	1053.4	**259.6**	-1040.4	1370.9	930.1	**136.3**	-1163.8	1468.0	1027.1	**233.4**	-1066.7	1520.8	1080.0	**286.3**	-1013.9
YA	364.8	**70.5**	-309.3	-448.8	408.1	**113.8**	-266.0	-405.6	391.8	**97.5**	-282.3	-421.8	410.7	**116.4**	-263.4	-403.0

OA	783.9	477.2	**-54.5**	-372.8	850.1	543.5	**11.8**	-306.6	859.1	552.5	**20.8**	-297.6	749.6	442.9	**-88.9**	-407.1
Condition three - SL																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	1373.4	857.0	**366.9**	-1070.5	1279.9	763.5	**273.4**	-1164.0	1456.8	940.4	**450.3**	-987.1	1299.9	783.5	**293.4**	-1144.0
YA	428.0	**134.5**	-255.4	-356.4	373.3	**79.7**	-310.9	-411.2	428.9	**135.3**	-254.6	-355.6	448.7	**155.1**	-234.8	-335.8
OA	710.6	417.6	**-45.4**	-351.6	699.5	406.4	**-56.6**	-362.8	629.0	336.0	**-127.0**	-433.2	623.6	330.6	**-132.4**	-438.6
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1233.5	1069.6	**358.1**	-851.3	1110.0	946.1	**234.6**	-974.8	1332.5	1168.5	**457.1**	-752.4	1213.2	1049.2	**337.8**	-871.7
YA	420.8	**122.7**	-251.7	-370.3	415.8	**117.6**	-256.8	-375.4	437.3	**139.1**	-235.3	-353.8	442.0	**143.8**	-230.6	-349.2
OA	703.2	415.9	**-95.0**	-367.6	795.8	508.5	**-2.4**	-275.0	748.1	460.8	**-50.1**	-322.7	703.6	416.3	**-94.6**	-367.2
Condition four - LS																
	P_AD-ST	P_AD-PV	P_AD-FAP	P_AD-END	P_B-ST	P_B-PV	P_B-FAP	P_B-END	P_E-ST	P_E-PV	P_E-FAP	P_E-END	P_T-ST	P_T-PV	P_T-FAP	P_T-END
icSCI	1300.0	812.9	**170.5**	-1139.2	1138.2	651.1	**8.6**	-1301.1	1311.2	824.1	**181.7**	-1128.0	1258.2	771.2	**128.7**	-1181.0
YA	408.5	**134.2**	-251.3	-351.9	435.7	**161.4**	-224.1	-324.7	446.7	**172.4**	-213.1	-313.7	464.9	**190.6**	-194.9	-295.5
OA	679.8	378.6	**-88.0**	-350.6	611.4	310.2	**-156.3**	-419.0	693.2	392.0	**-74.5**	-337.2	571.9	270.8	**-195.8**	-458.4
	NP_AD-ST	NP_AD-PV	NP_AD-FAP	NP_AD-END	NP_B-ST	NP_B-PV	NP_B-FAP	NP_B-END	NP_E-ST	NP_E-PV	NP_E-FAP	NP_E-END	NP_T-ST	NP_T-PV	NP_T-FAP	NP_T-END
icSCI	1318.3	1004.5	**288.2**	-876.4	1082.6	768.9	**52.5**	-1112.1	1258.8	945.0	**228.7**	-936.0	1212.9	899.1	**182.8**	-981.8
YA	398.4	**108.9**	-266.1	-365.0	459.6	**170.1**	-204.8	-303.7	460.2	**170.7**	-204.3	-303.1	440.8	**151.3**	-223.7	-322.5
OA	677.4	362.3	**-126.1**	-386.3	758.2	443.1	**-45.2**	-305.5	711.8	396.6	**-91.7**	-351.9	632.6	317.5	**-170.9**	-431.1

7.7 Discussion

This study is the first to investigate bimanual prehension after icSCI and how this differs to non-injured YA and OA. Taking the form of two experiments (manipulating object distance and object size) it aimed to examine how symmetrical and asymmetrical bimanual conditions influence bimanual prehension and synchrony between the limbs.

7.7.1 Transport phase

In agreement with hypothesis one and findings from unimanual literature (Mateo et al., 2015) participants with an icSCI produced longer (duration), slower (lower peak velocity) movements that YA and OA (figures 7.1 a and b in experiment one, and figures 7.7 a and b in experiment two). As suggested in study one (see chapter 6, section 6.7.1), the movement slowing may have occurred due to the reduction in triceps brachii and biceps brachii agonist-antagonist muscle activity (figure 7.6 and 7.12), as the triceps brachii serves to extend the elbow whilst the biceps brachii acts to stop further extension in non-injured participants (Koshland et al., 2005, Hughes et al., 2009). Therefore, the movement slowing may be a strategy adopted by participants with an icSCI, in order to decrease the reliance on the biceps brachii to stop further extension of the elbow, as faster movements require greater muscle activity in order to stop the movement (Hughes et al., 2009, Koshland et al., 2005). Another explanation for the motor slowing may be that participants with an icSCI slow their movements down, in order to maintain accuracy during the reach-to-grasp task, as per the speed accuracy trade off (Fitts, 1954, Mateo et al., 2015).

The EMG data (for both experiments) showed that following icSCI the triceps brachii and biceps brachii agonist-antagonist muscle activity is weaker than in non-injured participants. Thus, a novel muscle activity pattern is developed (in agreement with hypothesis two) to apply a braking force to the upper limb, and prevent further extension of the arm passed the location of the object. This suggests that neuroplasticity of spared fibres in the acute stages of injury, such as those of the CST (Oudega and Perez, 2012), has given rise to new muscle patterns being elicited to preserve the performance of the reach to grasp movement. The novel muscle strategy seen in participants with an icSCI supports the notion of motor redundancy (Koshland et al., 2005) following icSCI, as different muscle activation patterns were seen to non-injured YA and OA. Consistent with study one, YA produced peak muscle activity (anterior deltoid, biceps brachii, extensor digitorum superficialis, triceps brachii) closer to the time of PV than participants with an icSCI. Additionally, in condition two (FF) and three (NF) in experiment one (when reaching for the far object), and two (LL), three (SL) and four (LS) in experiment two (when reaching for the large object), OA produced peak muscle activity (anterior deltoid, extensor digitorum superficialis and triceps brachii), closer to PV than participants with an icSCI. In contrast to YA and OA, participants with an icSCI produced peak muscle activity closer to and after the start of FAP (corresponding to the phase when then limb is slowed down and becomes stationary).

Participants with an icSCI spent a longer proportion of the movement in the deceleration and final adjustment phase (figures 7.1 c-d and 7.7 c-d), and made more adjustments in these phases (figures 7.2 a-b and 7.8 a-b), when compared to YA and OA. This is consistent with findings in the unimanual prehension literature (Mateo et al., 2013, Hoffmann et al., 2006, de los Reyes-Guzmán et al., 2010, Laffont et al., 2000) and findings in study one (see chapter 6, section 6.7.1). Additionally, in experiment one OA relied more heavily on the deceleration phase than YA, but this group difference did not reach significance for the final adjustment phase as in previous research (Coats and Wann, 2012), which may be due to task differences (object placement not specified in the current study). In experiment two, the difference between YA and OA did not reach significance, however, as can be seen from figure 7.1c and 7.7c, in both experiments OA spent a longer proportion of the movement decelerating when compared to YA. Overall, the increased reliance on the deceleration phase for both participants with an icSCI and OA compared to YA, and final adjustment phase for participants with an icSCI compared to YA, suggests that online feedback for error correction is not utilised. The declines in proprioceptive abilities with aging and following icSCI, and subsequent increased reliance on visual feedback may explain this, although further testing would be needed to support this suggestion. This is because visual feedback of both limbs and objects at one time is not available until both limbs are closer to the object, therefore, leading to the participants with an icSCI and OA requiring more time in the deceleration and final adjustment phase (icSCI only) than YA to correct any errors induced when transporting the limbs (Coats and Wann, 2012).

A condition by group interaction for the number of adjustments in the final adjustment phase showed that participants with an icSCI and OA relied more heavily on the final adjustment phase in condition two (LL) than condition one (SS), as there was no main effect of condition for YA. This is consistent with findings discussed above, as the participants with an icSCI and OA rely more heavily on the final adjustment phase for error correction and subsequently produce more adjustments. The increase in number of adjustments when reaching to the large object may have occurred due to declines in hand opening ability with age (Holt et al., 2013) and following icSCI (Stahl et al., 2014). Thus, the larger object decreased the safety margin (difference between object size and MGA) for effective grasping and required more time in the final adjustment phase to ensure accurate finger and thumb placement around the object.

Alternatively (as suggested in study one), the longer proportion of the movement spent in the final adjustment phase following icSCI, may have occurred due to detriments in grip force modulation, via disruption of the CST. This is because the direct CM network of the CST, as well as premotor spinal interneurons in the cervical spinal cord, have shown activation during the dynamic phase of the precision grip (squeezing the index finger and thumb together) (Bennett and Lemon, 1996, Takei and Seki, 2013). Additionally, as those suffering from a icSCI were often older adults the natural declines in force modulation with age (Voelcker-Rehage and Alberts, 2005), could also have contributed to the increased propFAP to ensure accurate grip force is applied to the object prior to pick up. In order to test this in future research, the addition of force transducers on the object surface would give further insight into this control.

In experiment one the main effect of group did not reach significance for resultant path length, path length in the vertical direction and maximal wrist height, which differs from study one (chapter 6, section 6.7.1). However, as shown in figures 7.4 a and c participants with an icSCI produced movements with a longer resultant path length and higher maximal wrist height than non-injured participants. With regards to path length in experiment two, participants with an icSCI produced movements with a significantly greater resultant path length than YA and OA (figure 7.10a). Although not significant participants with an icSCI also produced bimanual movements with a greater path length in the vertical direction and maximal wrist height when compared to YA and OA (figures 7.10 b-c). These results from both experiments suggest that participants with an icSCI induce errors in the transport of the limb to the object and do not follow a direct path as in YA and OA. These errors could occur due to loss of proximal control, via to damage to the CST (Lemon et al., 1995), or due to loss of proprioceptive feedback. The increased wrist height agrees with previous unimanual research (de los Reyes-Guzmán et al., 2010, Mateo et al., 2013, Hoffmann et al., 2006, Laffont et al., 2000), that following injury to the cervical spinal cord, participants transport their limb above the object in order to avoid object collision.

With regards to object characteristics, increasing object distance resulted in prolonged movement time (figure 7.1a) and a higher peak velocity (figure 7.1b) (condition two, FF), which agrees with previous bimanual research in non-injured individuals, as both limbs were reaching to the far object (Mason and Bruyn, 2009). The condition by limb interaction for peak velocity was consistent with the findings by Mason and Bruyn (2009), as the limb reaching for the far object reached a higher peak velocity than the limb reaching for the near object in asymmetrical conditions (e.g. peak velocity for the P/LI limb in condition four (FN) was greater than in condition three (NF)).

For both propDT and propFAP (figure 7.1c-d) there was a significant condition by limb interaction, and subsequent investigations revealed that in asymmetrical conditions a greater proportion of the movement was spent in these two phases for the limb moving to the near object (e.g. P/LI limb in condition three (NF) when compared to condition two and four (FN and FF)). This increase in propDT and propFAP could be due to the limb reaching to the near object arriving first and hovering above the object whilst the opposite limb was transported to the far object, supporting research by Riek et al., (2003). The increase in propFAP was also accompanied by an increase in number of adjustments for the limb moving to the near object in asymmetrical conditions, which could be to avoid object collision.

Increasing object size resulted in a longer movement time (figure 7.7a) and proportion of movement time spent in the deceleration phase (figure 7.7c) (MT and propDT greater in LL), however, this does not agree with findings by Mason and Bruyn (2009), who found no main effect of object size, despite a similar object size being used (7cm). It also contradicts research in unimanual aiming as a longer movement time was seen when moving to small targets compared to large targets, due to higher accuracy demands (Bootsma et al., 1994). Having said this, the results for peak velocity (figure 7.7c) revealed no significant main effect of condition, which mirrors findings by Mason and Bruyn (2009). When looking further into the effects of object size on movement time, it is evident from figure 7.7a that participants with an icSCI showed a greater difference in movement time with regards to object size (LL compared to SS). This may have occurred as participants with an icSCI have previously been shown to have a reduced maximal hand opening (Stahl et al., 2014), thus, have a lower safety margin for successful finger and thumb placement around the object when compared to non-injured individuals. The increased movement time could be to allow a longer time period for successful digit placement around the large object compared to small object. This suggestion is supported by the condition by group interaction for propFAP, which shows that condition (LL greater than SS and LS) only had a significant main effect for participants with an icSCI and not YA or OA.

For the number of adjustments in the approach phase, a condition by limb interaction revealed that more adjustments were made in condition two (LL) compared to condition one (SS) and three (SL), by both the P/LI and NP/MI limb, with the additional difference between condition two (LL) and condition four (LS) for the NP/MI limb. Therefore, these results are consistent with the prolonged movement time and deceleration time (propDT) when moving to the large objects.

Increasing object size also influenced resultant path length as condition two (LL) resulted in a longer resultant path length (figure 7.10a) compared to condition one (SS) and condition four (LS), despite object distance not being manipulated between conditions. When looking at figure 7.10a it is evident that the difference between conditions is more pronounced for participants with an icSCI, which may be another explanation for the increased movement time seen in condition two. Additionally, participants with an icSCI showed an increased maximal wrist height when reaching for the two large objects compared to condition one (SS) (figure 7.10c), which may have contributed to the increased resultant path length.

For all muscles a condition by group interaction emerged showing that for YA and OA there was no significant main effect of condition, however, for participants with an icSCI there was, which is consistent with the condition by group interaction seen for propFAP. The results of this interaction showed that peak muscle activity (anterior deltoid, biceps brachii, triceps brachii) in condition one (SS) was closer to PV than in the other three conditions (which were closer to the start of FAP). Therefore, these results support the kinematic results of an increased reliance on the final adjustment phase in conditions when the large object is being grasped. The increased muscle activity seen may have occurred to hold the limb (‘hovering’) above the object whilst the finger and thumb were placed accurately around the object.

7.7.2 Grasp phase

The results from experiment one and two showed that there was no significant main effect of group for MGA (figure 7.3a and 7.9a). In experiment one, a limb by group interaction showed that participants with an icSCI had a reduced MGA for the MI limb compared to LI limb, which may be due to greater muscle paralysis (e.g. flexor carpi ulnaris, extensor carpi ulnaris, flexor digitorum superficialis and extensor digitorum superficialis) in the MI limb and therefore reduced hand opening (Stahl et al., 2014). However, the OA had a reduced MGA for the P compared to NP limb suggesting a larger MGA formation for the NP limb to provide a greater safety margin to ensure successful finger and thumb placement around the object and object collision avoidance (Marteniuk et al., 1990).

In both experiments, participants with an icSCI produced MGA earlier in the movement than YA and OA (figure 7.3b and 7.9b). The earlier MGA formation seen in participants with an icSCI resulted in the transport and grasp phases being performed sequentially when compared to YA and OA (figure 7.3c and 7.9c), and this temporal dissociation between the two phases agrees with previous unimanual research (Mateo et al., 2013), and results from study one. The earlier MGA formation following icSCI may be a strategy to allow more time for error correction and successful finger and thumb placement around the objects (Marteniuk et al., 1990). As suggested in experiment one, introducing friction to the object surface may reduce the differences seen between groups, as higher object friction increases the effective zone for grasping the object (Holt et al., 2013). Overall the group differences seen between participants with an icSCI and non-injured participants, e.g. earlier hand opening and increased propFAP, may be due to disruption of the CST, which has been shown to detriment preshaping of the hand in primates (Sasaki et al., 2004) and grip force modulation (Bennett and Lemon, 1996, Takei and Seki, 2013) (section 2.2 and 2.4).

In experiment one, MGA was reached earlier in the movement when reaching to the near compared to far object. This resulted in a significant condition by limb interaction, which showed that in asymmetrical conditions, MGA was formed earlier in the movement for the limb reaching to the near compared to far object (e.g. P/LI limb compared to NP/MI limb in condition three, NF). For participants with an icSCI, this resulted in peak extensor digitorum superficialis activity being closer to PV in condition one (NN), three (NF) and four (FN) compared to condition two (FF), supporting the earlier MGA formation when reaching to the near object (figure 7.3b).

In experiment two, the results for MGA (figure 7.9a) showed that despite injury to the cervical spinal cord participants with an icSCI were still able to scale MGA to object size (larger MGA in condition two than one, three and four), consistent with findings by Stahl et al., (2014) in unimanual research. Object size influenced the timing of MGA (figure 7.9b) as earlier hand opening occurred when moving to the small object in asymmetrical conditions (e.g. P/LI limb earlier than NP/MI limb in condition three (SL)), with no difference between limbs in symmetrical conditions, as revealed by a condition by limb interaction. The earlier hand opening towards the small object resulted in greater coupling between the transport and grasp phases (time of MGA formation and time of peak deceleration) for all groups when reaching for the small object compared to the large object (e.g. P/LI limb in condition three compared to NP/MI limb) as shown by a condition by limb interaction (figure 7.9c). This suggests that when reaching for the large object the limb is transported to the location of the object before the hand is opened to MGA and successful grip around the object is formed.

7.7.3 Interlimb synchrony

For both experiments (figures 7.5 a-d and 7.11 a-d) participants with an icSCI produced less synchronous movements when compared to YA and OA at the start of the movement, at peak velocity, at the start of the final adjustment phase and end of the movement (in agreement with hypothesis three). One suggestion is that this may be due to their due to their loss of sensory function, and particularly proprioception, that has been shown to influence synchrony in non-injured control participants (Bruyn and Mason, 2009). This subsequently increases their reliance on visual feedback, which naturally produces asynchrony between the limbs as it is not possible to fixate both limbs/objects at the same time (Mason and Bruyn, 2009, Riek et al., 2003). This theory would need further testing to specifically investigate the importance of visual feedback following icSCI.

As seen in figures 7.5c and 7.11c all participants used the final adjustment phase to improve synchrony of their upper limbs when picking up the objects. This suggests that despite disparate abilities of the two limbs following icSCI and disruption to the CST, participants still aimed to complete the task in a synchronous fashion (despite no specific instruction to do so). Therefore a level of bimanual coordination is still retained, which has the potential to be utilised in bimanual therapy and subsequently improve upper limb function and performance of activities of daily living. As participants in this study were in the acute stages of injury, and this is associated with the greatest neuroplasticity (Curt et al., 2008), integrating bimanual therapy at this early stage could induce the greatest gains in functional recovery. Further support for the retention of bimanual coordination is evident from the CAHAI-9 scores (see table 5.0 in chapter 5) as eight out of the eighteen participants with an icSCI (ASIA C-D) scored full marks on the CAHAI-9, therefore had complete independence (performing each of the nine items safely and timely) when performing bimanual tasks even though bimanual movements were not trained in conventional therapy (unimanual based practice).

In experiment one, at the start of the final adjustment phase a significant condition by group interaction emerged and subsequent investigations showed that for YA and OA there was no significant main effect of condition. However, for participants with an icSCI the asymmetrical conditions (NF=270ms and FN=239ms) were less synchronous than the symmetrical conditions (NN=142ms and FF=183ms) (figure 7.5c). Object size also influenced interlimb synchrony, but only at the end of the movement, as condition three (SL, 96ms) resulted in greater asynchrony between the limbs than condition one (SS, 36ms). In addition, although not significant, condition four (LS, 57ms) was also less synchronous than condition one. As evident in figure 7.11d, the difference in synchrony between asymmetrical conditions was greater for participants with an icSCI than YA and OA. Overall, these findings of asynchrony in asymmetrical conditions support previous research in non-injured participants (Mason and Bruyn, 2009, Riek et al., 2003, Bingham et al., 2008), but also support the idea that participants with an icSCI rely more heavily on visual feedback to perform bimanual movements, as the inability to visually fixate both hands and objects in asymmetrical conditions led to greater asynchrony between the limbs. This should be tested further in future research in order to fully understand the role of vision in bimanual prehension following icSCI.

7.8 Conclusion

Consistent with findings in study one participants with an icSCI produced reach to grasp movements of a longer duration, lower peak velocity and with an increased reliance on the deceleration phases than YA and OA. Additionally, participants with an icSCI spent a greater proportion of the movement time in the final adjustment phase compared to YA, but the difference to OA was not significant in experiment two. Participants with an icSCI were still able to scale their MGA to object size, but reached MGA earlier in the movement than both YA and OA, resulting in the transport and grasp phases of the movement being performed sequentially.

Object distance and object size influenced the transport and grasp kinematics of bimanual movements in a similar fashion to unimanual movements, e.g. prolonged movement time and proportion of the movement spent in the final adjustment phase when reaching for the near or large object, and earlier hand opening (MGA formation) when reaching to the near or small object. However, increasing object size posed greater task difficulty to those with an icSCI (e.g. prolonged movement time and greater propFAP), which may be due to their reduced ability to maximally open the hand.

In terms of muscle activity, participants with an icSCI showed novel muscle patterns (consistent with study one) in that they reached peak muscle activity later in the movement than non-injured participants, which is likely to be a strategy to apply a braking force to the upper limb, due to loss of triceps brachii and biceps brachii agonist-antagonist muscle activity. This motor redundancy suggests that neuroplasticity (in the acute stages of injury) has given rise to novel muscle patterns in order for the performance of the reach to grasp movement to preserved.

In both experiments participants with an icSCI produced bimanual movements with greater asynchrony between the limbs than YA and OA, which could be due to their increased reliance on visual feedback, although this would need further testing. Despite the reduction in synchrony between the limbs participants with an icSCI utilised the final adjustment phase to decrease the asynchrony between the limbs, a pattern which was evident in both YA and OA. This suggests that despite bimanual deficits following icSCI the participants aimed to complete the task in a synchronous fashion and a level of bimanual coordination is retained, which supports the integration of bimanual movements into therapy. The next chapter will investigate the differences seen between unimanual and bimanual conditions in order to provide further understanding of bimanual control following icSCI.

Chapter 8 Study three

8.1 Introduction

So far the studies in this thesis have addressed how unimanual and bimanual prehension following icSCI differs to non-injured participants following icSCI. However, the comparison between unimanual and bimanual prehensile movements has not been made. This will further enhance the knowledge of bimanual control following icSCI, which will help to guide rehabilitation.

Previous investigations in non-injured individuals have shown that limb performance differs between unimanual and symmetrical bimanual conditions in that bimanual movements take longer to complete, have lower peak velocities, and have larger maximum grasp apertures than unimanual movements (Kelso et al., 1979, Jackson et al., 1999, Marteniuk et al., 1984). This is collectively known as bimanual cost and is suggested to emerge in order to maintain synchrony between the limbs during bimanual movements (Jackson et al., 1999).

The purpose of this study was to compare unimanual and bimanual prehensile actions in individuals with an icSCI and how this differs to both young, and older non-injured control participants. In this study the following hypotheses were tested (1) individuals with an icSCI will exhibit spatially and temporally different kinematic parameters, e.g. longer movement time and more adjustments, during reach to grasp actions compared to non-injured controls (young adults and older adults), and (2) that bimanual actions will be longer and slower than unimanual actions for all participants (icSCI and non-injured).

8.2 Methods

8.2.1 Participants

Eighteen participants (table 5.0) with an icSCI (Mean age=61.61±15.24 years, 14 right handed), sixteen younger adults (mean age=23.6±4.54 years, 14 right handed) and sixteen older adults (Mean age=71±7.2 years, 12 right handed) volunteered for participation in this study. Further detail can be found in the general methods chapter (chapter 5, section 5.2.1).

8.2.2 Task

All details regarding the specifics of the task are presented in chapter 5 (section 5.3.2). The object/s (3x3x1.8cm) were placed at 50% (Near) of each individual’s maximal reach distance. Therefore the study consisted of twenty four trials; eight trials with the preferred/less impaired limb (P/LI), eight trials with the non-preferred/more impaired limb (NP/MI) and eight bimanual symmetrical trials (B).

8.2.3 Dependent variables and statistical analysis

Description of all kinematic and EMG analysis as well as dependent variables and statistical analysis is presented in chapter 5 (section 5.3.3 and 5.3.4). For the kinematic and EMG data a series of mixed repeated measures ANOVA's were performed for each dependent variable to determine the main effects of group (3 - icSCI, YA, OA), condition (2 - unimanual, bimanual) and limb (2 - P/LI, NP/MI). To investigate a condition by group interaction limb was collapsed and one-way ANOVAs were performed to explore whether the difference between groups reached significance. Following this, paired t-tests were performed to determine whether the difference between limbs reached significance for each group. To explore a limb by group interaction condition was collapsed and one-way ANOVAs for each limb were performed to determine any significant differences between groups. Paired t-tests were then performed to explore whether the difference between limbs reached significance for each group.

8.3 Results

8.3.1 Movement time

Figure 8.0a clearly shows that participants with an icSCI (M=1581ms) produced movements of a longer duration than YA (M=754ms) and OA (M=932ms) [$F(2,46)=27.62$, $p<0.001$, $\eta^2=0.55$] with no significant difference between YA and OA ($p>0.05$). There was no significant main effect of limb [$F(1,46)=0.17$, $p>0.05$, $\eta^2=0.004$] , however, a significant main effect of condition emerged [$F(1,46)=7.579$, $p<0.01$, $\eta^2=0.14$] with significantly longer MT when reaching bimanually (M=1210ms) compared to unimanually (M=968ms). No significant interactions emerged.

8.3.2 Peak velocity

As expected, participants with an icSCI (M=506mm/s) reached significantly lower PV than YA (M=707mm/s) [$F(2,43)=9.90$, $p<0.001$, $\eta^2=0.32$], with no significant difference between icSCI and OA or YA and OA ($p>0.05$) (figure 8.0b). There was no significant main effect of limb [$F(1,43)=2.29$, $p>0.05$, $\eta^2=0.05$] or condition [F(1,43=0.04, $p>0.05$, $\eta^2=0.001$] and no significant interactions emerged.

8.3.3 Proportion of movement time spent decelerating

Participants with an icSCI (M=73.89%) spent a longer proportion of the movement decelerating than YA (M=61.37%) and OA (M=67.04%) [$F(2,43)=19.94$, $p<0.001$, $\eta^2=0.48$] with no significant difference between YA and OA ($p>0.05$) (figure 8.0c). There was no significant main effect of limb [$F(1,43)=0.011$, $p=0.916$, $\eta^2=0.001$] but a significant main effect of condition emerged [$F(1,43)=23.64$, $p<0.001$, $\eta^2=0.36$] with longer propDT when reaching and grasping bimanually (M=69.06%) than unimanually (M=65.80%). No significant interactions emerged.

8.3.4 Proportion of movement time spent in the final adjustment phase

Figure 8.0d shows that in agreement with the longer propDT participants with an icSCI (M=30.27%) spent a longer proportion of the movement in final adjustment time than YA (M=11.66%) [$F(2,43)=7.01$, $p<0.01$, $\eta^2=0.25$] , however, no significant differences emerged between icSCI and OA or YA and OA ($p>0.05$). There was no significant main effect of limb [$F(1,43)=0.85$, $p>0.05$, $\eta^2=0.02$] but a significant main effect of condition emerged [$F(1,43)=7.93$, $p<0.01$, $\eta^2=0.16$] with longer propFAP when reaching and grasping bimanually (M=23.1%) when compared to unimanually (M=19.3%).

A significant condition by group interaction emerged [$F(2,43)=4.31$, $p<0.05$, $\eta^2=0.17$] and subsequent paired t-tests performed for each group (with limb collapsed) revealed that for participants with an icSCI and YA there was no significant difference in propFAP between unimanual and bimanual conditions, but there was a significant difference for OA [$t(14)=-3.14$, $p<0.01$] with longer propFAP in the bimanual condition (unimanual=17.05%, bimanual=26.27%). The two one-way ANOVA's (with limb collapsed) for each condition revealed that in the unimanual [$F(2,49)=8.04$, $p<0.01$, $\eta^2=0.25$] and bimanual condition [$F(2,46)=6.47$, $p<0.01$, $\eta^2=0.22$] there was a significant main effect of group as participants with an icSCI (unimanual=28.15%, bimanual=33.94%) produced propFAP greater than YA (unimanual=10.41%, bimanual=12.95%) in both conditions, and OA (M=16.89%) in the unimanual condition only.

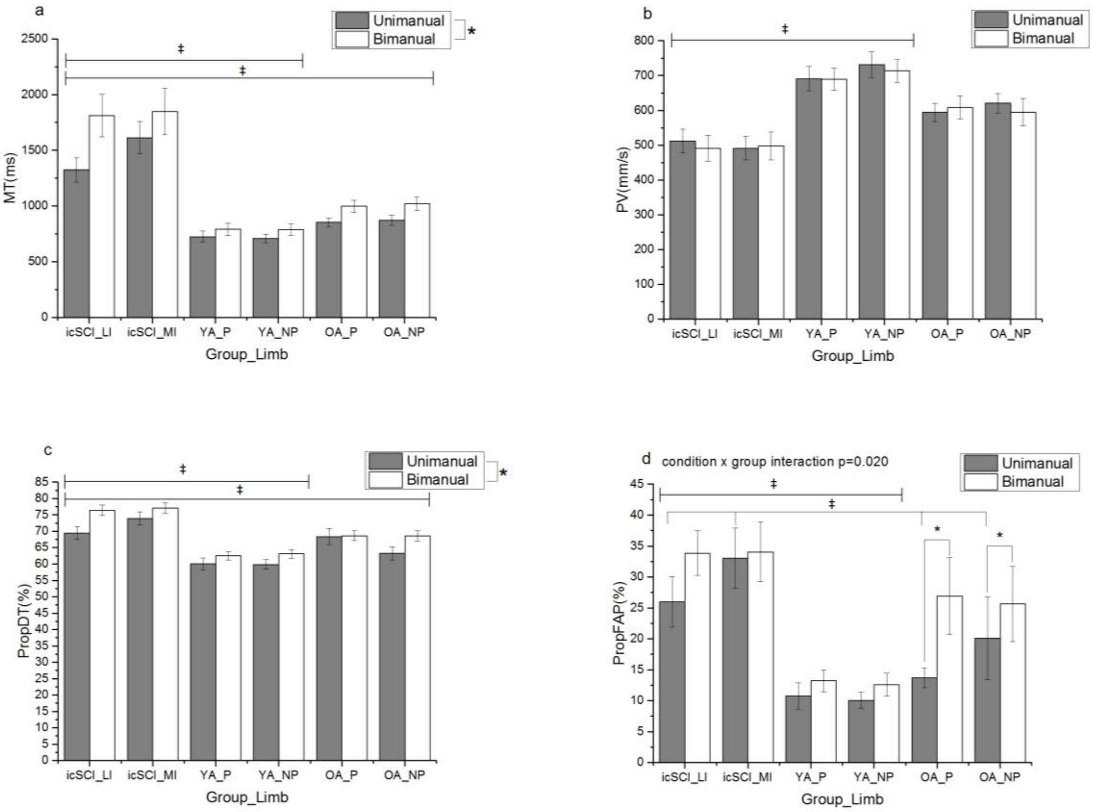

Figure 8.0: Group and limb means (±standard error) for movement time (MT) (a), peak velocity (PV) (b), proportion of movement time spent decelerating (propDT) (c), proportion of movement time spent in final adjustment phase (propFAP) (d) for unimanual (grey) and bimanual (white) conditions. (* denotes significant difference between conditions and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

8.3.5 Number of adjustments in the approach phase

Participants with an icSCI (M=3.43) produced significantly more adjustments than YA (M=0.53) and OA (M=1.36) [$F(2,46)=34.67$, $p<0.001$, $\eta^2=0.60$] with no significant difference between YA and OA ($p>0.05$) (figure 8.1a). There was also a significant main effect of condition [$F(1,46)=6.71$, $p<0.05$, $\eta^2=0.13$] with more adjustments made in the bimanual (M=2.03) compared to unimanual condition (M=1.52).

However, there was no significant main effect of limb [$F(1,46)=1.37$, $p>0.05$, $\eta^2=0.03$] and no significant interactions emerged.

8.3.6 Number of adjustments in the final adjustment phase

As shown by figure 8.1b the significant main effect of group continued in the final adjustment phase with more adjustments made by participants with an icSCI (M=7.47) compared to YA (M=1.21) or OA (M=2.10) [$F(2,46)=11.08$, $p<0.001$, $\eta^2=0.33$] and no significant difference between YA and OA ($p>0.05$). There was no significant main effect of condition [$F(1,46)=3.29$, $p>0.05$, $\eta^2=0.07$] or limb [$F(1,46)=1.30$, $p>0.05$, $\eta^2=0.03$] but a significant limb by group interaction emerged [$F(2,46)=3.53$, $p<0.05$, $\eta^2=0.13$].

To explore the limb by group interaction one-way ANOVAs (condition collapsed) for each limb were performed and revealed that for the P/LI limb [$F(2,49)=9.35$, $p<0.001$, $\eta^2=0.28$] and NP/MI limb [$F(2,49)=12.82$, $p<0.001$, $\eta^2=0.35$] there was a significant difference between groups as participants with an icSCI (LI=6.96, MI=7.99) made more adjustments than YA (P=1.30, NP=1.13) and OA (P=2.16, NP=2.03). Paired t-tests for each group revealed that for all three (icSCI [$t(17)=-1.88$, $p>0.05$], YA [$t(15)=0.98$, $p>0.05$], OA [$t(15)=1.10$, $p>0.05$]) groups there was no significant difference in number of adjustments made between the limbs.

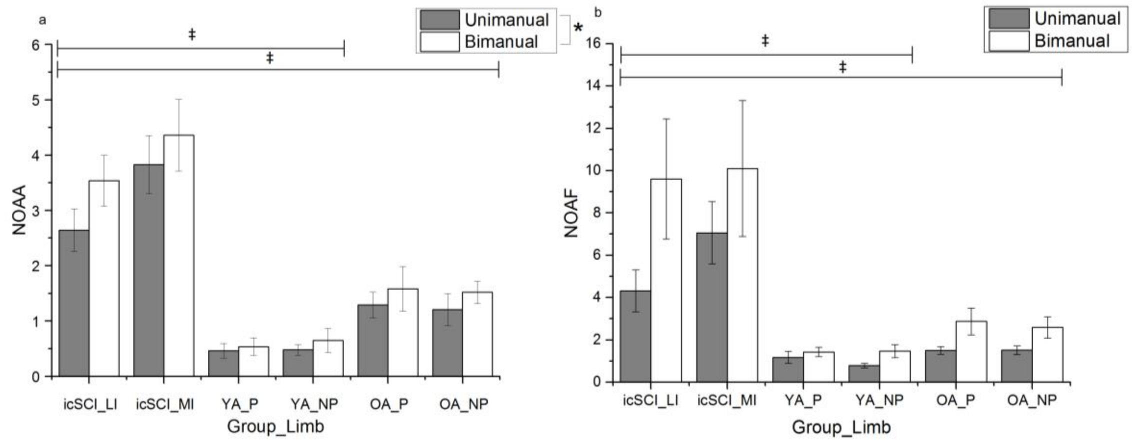

Figure 8.1: Group and limb means (±standard error) for number of adjustments in the approach phase (NOAA) (a), and final adjustment phase (NOAF) (b) for unimanual (grey) and bimanual (white) conditions. (* denotes significant difference between conditions and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred

limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

8.3.7 Maximum Grasp Aperture

There was no significant main effect of group [$F(2,43)=1.46$, $p>0.05$, $\eta^2=0.06$] or limb [$F(1,43)=0.02$, $p>0.05$, $\eta^2=0.001$]. However, as shown in figure 8.2a, a significant main effect of condition emerged [$F(1,43)=34.73$, $p<0.001$, $\eta^2=0.45$] with smaller MGA in the unimanual (M=9.3cm) compared to bimanual condition (M=9.7cm). No significant interactions emerged.

8.3.8 Time of maximum grasp aperture as a percentage of movement time

Participants with an icSCI (M=51.43%) reached MGA earlier in the movement when compared to YA (M=63.96%) and OA (M=59.50%) [$F(2,43)=13.13$, $p<0.001$, $\eta^2=0.38$] but no significant difference between YA and OA emerged ($p>0.05$) (figure 8.2b). There was no significant main effect of limb [$F(1,43)=0.79$, $p>0.05$, $\eta^2=0.02$] but a significant main effect of condition emerged [$F(1,43)=14.05$, $p<0.01$, $\eta^2=0.25$] as MGA was reached significantly earlier in bimanual (M=55.5%) compared to unimanual reaching (M=61.09%). No significant interactions emerged.

8.3.9 Transport and Grasp coupling

The transport and grasp phases were significantly less coupled for participants with an icSCI (M=223ms) compared to YA (M=39ms) and OA (M=87ms) [$F(2,43)=15.89$, $p<0.001$, $\eta^2=0.43$] and the difference between YA and OA did not reach significance ($p>0.05$) (figure 8.2c). There was no significant main effect of condition [$F(1,43)=3.99$, $p>0.05$, $\eta^2=0.09$] or limb [$F(1,43)=0.45$, $p>0.05$, $\eta^2=0.01$] and no significant interactions emerged.

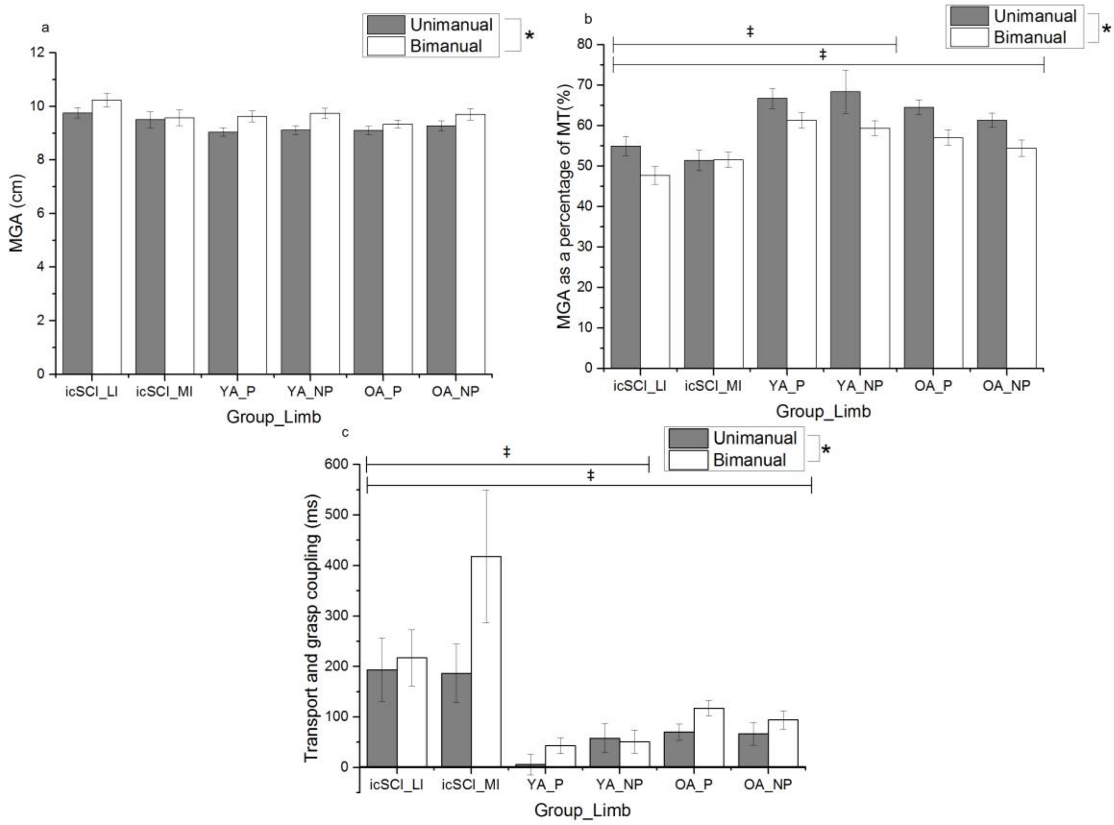

Figure 8.2: Group and limb means (±standard error) for maximum grasp aperture (MGA) (a), time of maximum grasp aperture as a percentage of movement time (MGA as a percentage of MT) (b) and transport and grasp coupling (c) for unimanual (grey) and bimanual (white) conditions. (* denotes significant difference between conditions and ‡ represents a significant difference between groups),(icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

8.3.10 Path Length

A significant main effect of group emerged [F(2,43)=5.53, p<0.01, η^2=0.21] as participants with an icSCI (M=29.8cm) had a longer resultant path length than YA (M=24.8cm) and OA (M=23.9cm), as shown in figure 8.3a. There was no significant main effect of condition [F(1,43)=0.11, p>0.05, η^2=0.003] or limb [F(1,43)=1.06, p>0.05, η^2=0.02] and no significant interactions emerged.

When looking at path length in the vertical direction (z) there was a significant main effect of group [F(2,43)=3.58, p<0.05, η^2=0.14] as participants with an icSCI

(M=15.3cm) had a greater path length in z than YA (M=8.9cm) (figure 8.3b). There was no significant difference between participants with an icSCI and OA, or YA and OA ($p>0.05$). No significant main effect of condition [$F(1,43)=0.22$, $p>0.05$, $\eta^2=0.005$] or limb [$F(1,43)=0.09$, $p>0.05$, $\eta^2=0.002$] or interactions emerged.

As shown in figure 8.3c participants with an icSCI (M=19.1cm) also produced movements with a greater wrist height than YA (M=11.3cm) and OA (M=13.3cm) [$F(2,43)=9.57$, $p<0.001$, $\eta^2=0.31$]. There was no significant main effect of condition [$F(1,43)=0.01$, $p>0.05$, $\eta^2=0.001$] or limb [$F(1,43)=0.18$, $p>0.05$, $\eta^2=0.004$] and no significant interactions emerged.

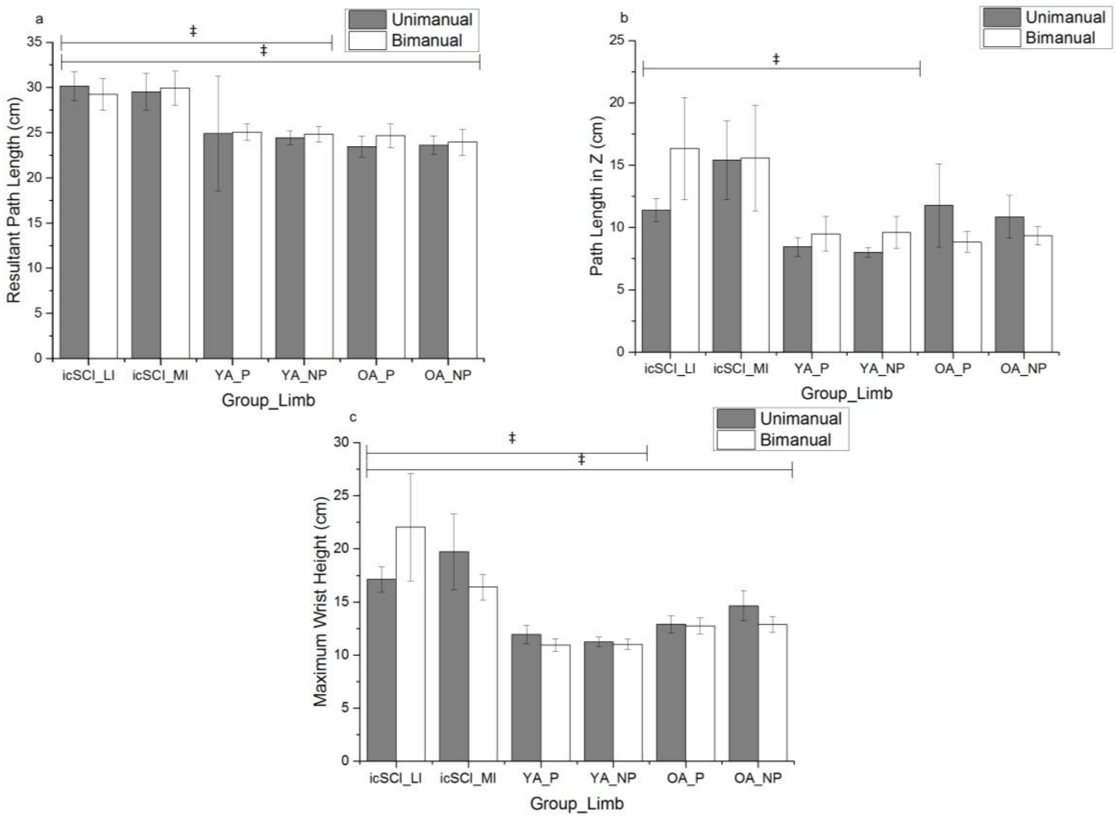

Figure 8.3: Group and limb means (±standard error) for resultant path length (a), path length in the vertical direction (z) (b) and maximum wrist height (c) for unimanual (grey) and bimanual (white) conditions. (‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

8.4 EMG analysis

For the timing of peak muscle activity in relation to kinematic events it is clear from table 6.0 in chapter 6 (section 6.4) and table 7.0 in chapter 7 (section 7.4) that for all participants this occurs between peak velocity and the start of the final adjustment phase. Therefore this was the focus of the subsequent statistical analyses.

8.4.1 Anterior Deltoid

For PV [$F(2,37)=13.78$, $p<0.001$, $\eta^2=0.43$] and start of FAP [$F(2,37)=4.48$, $p<0.05$, $\eta^2=0.20$] there was a significant main effect of group as YA (M=76ms) produced peak anterior deltoid activity closer to PV than participants with an icSCI (M=454ms) and OA (M=317ms), but participants with an icSCI (M=-167ms) and OA (M=-130ms) produced peak anterior deltoid closer to the start of FAP than YA (M=-306ms). The main effect of condition (PV [$F(1,37)=0.11$, $p>0.05$, $\eta^2=0.003$], FAP [$F(1,37)=0.06$, $p>0.05$, $\eta^2=0.002$]) and limb (PV [$F(1,37)=1.12$, $p>0.05$, $\eta^2=0.03$], FAP [$F(1,37)=1.31$, $p>0.05$, $\eta^2=0.03$]) did not reach significance and no significant interactions emerged for either kinematic parameter.

8.4.2 Biceps Brachii

A significant main effect of group emerged (PV [$F(2,37)=10.81$, $p<0.001$, $\eta^2=0.37$], FAP [$F(2,37)=3.45$, $p<0.05$, $\eta^2=0.16$]) as YA (M=68ms) produced peak biceps brachii activity closer to the time of PV than participants with an icSCI (M=405ms) and OA (M=314ms), and participants with an icSCI (M=-217ms) and OA (M=-133ms) produced peak biceps brachii activity closer to the start of FAP than YA (M=-314ms). There was no significant main effect of condition (PV [$F(1, 37)=0.12$, $p>0.05$, $\eta^2=0.003$], FAP [$F(1,37)=0.05$, $p>0.05$, $\eta^2=0.001$]) or limb (PV [$F(1,37)=0.50$, $p>0.05$, $\eta^2=0.01$], FAP [$F(1,37)=0.44$, $p>0.05$, $\eta^2=0.01$] and no significant interactions emerged.

8.4.3 Extensor Digitorum Superficialis

YA (M=95ms) produced peak extensor digitorum superficialis (EDS) activity closer to PV than participants with an icSCI (M=489ms) and OA (M=322ms) [$F(2,37)=12.64$, $p<0.001$, $\eta^2=0.41$]. Additionally, participants with an icSCI (M=-286ms) and OA (M=-125ms) produced peak extensor digitorum superficialis activity closer to the start of FAP than YA (M=-286ms). The main effects of condition (PV [$F(1,37)=0.11$, $p>0.05$, $\eta^2=0.003$], FAP [$F(1,37)=0.04$, $p>0.05$, $\eta^2=0.001$] and limb (PV [$F(1,37)=0.01$, $p>0.05$, $\eta^2=0.002$], FAP [$F(1,37)=0.02$, $p>0.05$, $\eta^2=0.001$] did not reach significance and no significant interactions emerged.

8.4.4 Triceps Brachii

For PV there was a significant main effect of group [$F(2,37)=10.73$, $p<0.01$, $\eta^2=0.37$] as YA (M=86ms) produced peak triceps brachii activity closer to PV than participants with an icSCI (M=373ms) and OA (M=226ms). The main effect of group did not reach significance for the start of FAP [$F(2,37)=1.00$, $p>0.05$, $\eta^2=0.05$] as all groups were at a similar time difference from FAP (icSCI=-249ms, YA=-295ms, OA=-221ms). There was no significant main effect of condition (PV [$F(1,37)=2.49$, $p>0.05$, $\eta^2=0.06$], FAP [$F(1,37)=1.10$, $p>0.05$, $\eta^2=0.03$]) or limb (PV [$F(1,37)=1.24$, $p>0.05$, $\eta^2=0.03$], FAP [$F(1,37)=1.15$, $p>0.05$, $\eta^2=0.03$] and no significant interactions emerged.

8.4.5 Agonist-Antagonist muscle activity patterns

YA (M=-3ms) and OA (M=79ms) produced peak triceps brachii activity and lowest biceps brachii activity at a closer time point than participants with an icSCI (M=436ms) [$F(2,37)=6.53$, $p<0.01$, $\eta^2=0.26$] (figure 8.4). The main effect of limb did not reach significance [$F(1,37)=0.82$, $p>0.05$, $\eta^2=0.02$] but the main effect of condition was significant [$F(1,37)=6.12$, $p<0.05$, $\eta^2=0.14$] as peak triceps brachii activity and lowest biceps brachii activity occurred at a closer time point in the unimanual (M=82ms) compared to bimanual condition (M=259ms).

A significant condition by group interaction also emerged [$F(2,37)=6.11$, $p<0.05$, $\eta^2=0.25$] and subsequent one-way ANOVAs (limb collapsed) performed for each condition showed that for unimanual condition there was no significant difference between groups [$F(2,42)=2.24$, $p>0.05$, $\eta^2=0.10$], but for the bimanual condition [$F(2,42)=8.51$, $p<0.05$, $\eta^2=0.30$] participants with an icSCI (M=704ms) produced peak triceps brachii activity and lowest biceps brachii activity with a greater time difference than YA (M=-18ms) and OA (M=88ms). Paired t-tests for each group showed that for YA [$t(15)=0.82$, $p>0.05$] and OA [$t(12)=-0.26$, $p>0.05$] there was no significant difference between unimanual and bimanual conditions. However, for participants with an icSCI [$t(13)=-2.90$, $p<0.05$] peak triceps brachii activity and lowest biceps brachii activity occurred at a closer time point in the unimanual (M=155ms) compared to bimanual condition (M=704ms).

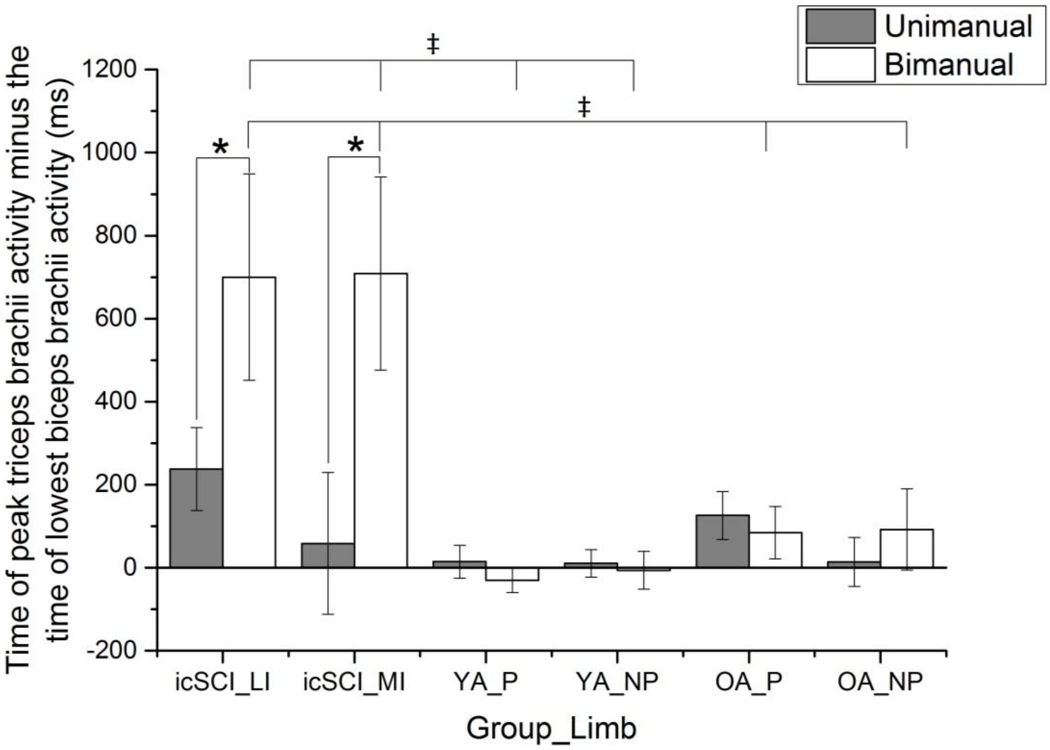

Figure 8.4: Group and limb means (±standard error) for the time difference between the timing of peak triceps brachii activity and lowest biceps brachii activity in unimanual (grey) and bimanual (white) conditions. (* denotes significant difference between conditions and ‡ represents a significant difference between groups), (icSCI_LI = incomplete cervical Spinal Cord Injury less impaired limb, icSCI_MI = incomplete cervical Spinal Cord Injury more impaired limb, YA_P = non-injured younger adults preferred limb, YA_NP = non-injured younger adults non-preferred limb, OA_P = non-injured older adults preferred limb, OA_NP = non-injured older adults non-preferred limb).

8.4.6 Summary of results

Participants with an icSCI produced movements of a longer duration (figure 8.0a) and spent a longer proportion of the movement in the deceleration phase (figure 8.0c) compared to YA and OA. They also reached a lower peak velocity (figure 8.0b) and spent a longer proportion of the movement in the final adjustment phase (figure 8.0d) when compared to YA. A condition by group interaction for propFAP showed that for the unimanual condition participants with an icSCI spent a greater proportion of the movement in the final adjustment phase than YA and OA, but in the bimanual condition the group difference between icSCI and OA did not reach significance.

In agreement with the prolonged deceleration and final adjustment phase participants with an icSCI made more adjustments in the approach (figure 8.1a) and final adjustment phases (figure 8.1b) when compared to YA and OA. Analysis of a limb by group interaction for the number of adjustments in the final adjustment phase showed that participants with an icSCI made more adjustments than YA and OA for both the P/LI limb and NP/MI limb. Participants with an icSCI also produced movements with a longer resultant path length than YA and OA (8.3a). Participants with an icSCI produced movements with a longer path length in z than YA (figure 8.4b), and with a greater maximum wrist height than YA and OA (figure 8.4c).

With regards to the grasp phase there was no significant main effect of group for MGA (figure 8.2a), but participants with an icSCI produced MGA earlier in the movement than YA and OA (figure 8.2b), which resulted in decoupling of the transport and grasp phases (figure 8.2).

When looking at reaching type (unimanual vs bimanual) the results showed that bimanual movements were longer (duration) (figure 8.0a) than unimanual movements with an increased proportion of the movement spent in the deceleration (figure 8.0c) and final adjustment phase (figure 8.0d) when compared to unimanual movements for all participants. In agreement with the prolonged deceleration phase more adjustments were made in the bimanual than unimanual condition for the approach phase (figure 8.1a), but the main effect of condition did not reach significance for the number of adjustments in the final adjustment phase (figure 8.1b). A condition by group interaction for the number of adjustments in the final adjustment phase showed that for YA and participants with an icSCI there was no significant difference between conditions, however, for OA more adjustments were made in the bimanual compared to unimanual condition. In bimanual conditions MGA was larger (figure 8.2a) and formed earlier in the movement than in the unimanual condition (figure 8.2b), but there was no significant main effect of condition in terms of transport and grasp coupling (figure 8.2c). There was no significant main effect of limb for any of the kinematic dependent variables.

For all muscles tested (anterior deltoid, biceps brachii, extensor digitorum superficialis and triceps brachii) YA produced peak muscle activity closer to the time of PV than participants with an icSCI and OA. In contrast, participants with an icSCI and OA produced peak muscle activity closer to the start of the final adjustment phase compared to YA (main effect of group did not reach significance for the triceps brachii). Reaching type did not have a significant main effect on timing for muscle activity for any of the muscles tested. Finally, the timing between the peak agonist (triceps brachii) and lowest antagonist (biceps brachii) muscle activity was also weaker for participants with an icSCI compared to YA and OA.

8.5 Discussion

This study is the first to compare unimanual and bimanual prehensile actions in individuals with an icSCI, and how this differs to both younger, and older non-injured participants. To avoid repetition of discussion relating to the group differences for kinematic and EMG analysis, refer to sections 6.7.1 and 6.7.2 of chapter 6 and sections 7.7.1 and 7.7.2 of chapter 7.

The emergence of a condition by group interaction for propFAP and subsequent showed that the group difference between participants with an icSCI and OA did not reach significance for the bimanual condition. Additionally, older adults spent a greater proportion of the movement in the final adjustment phase in bimanual conditions than unimanual conditions, whereas, participants with an icSCI showed similar propFAP in both unimanual and bimanual conditions. The increased reliance on the final adjustment phase (figure 8.0d) seen in participants with an icSCI in both unimanual and bimanual conditions, and OA (although to a lesser extent than icSCI) in bimanual conditions, could be explained by a loss in proprioceptive abilities that has already been documented in older adults (Seidler and Stelmach, 1995) and deafferented patients (Gordon et al., 1995). The decrease in proprioceptive feedback regarding limb position leads to an increased reliance on visual feedback for error correction/successful grip formation, which can only be obtained when vision of the limb in relation to the object is available, therefore explaining the increased amount of time needed in the final adjustment phase. The difference for OA between the unimanual and bimanual movements may have occurred as bimanual conditions need shifts in visual fixation between the limbs in order to obtain the relevant information for error correction, thus increasing the amount of time spent in the final adjustment phase.

When focusing on the comparison between unimanual and bimanual prehension the findings of this study support previous research in the non-inured population (Kelso et al., 1979, Jackson et al., 1999), and extend them to individuals with an icSCI. Overall in the transport phase bimanual movements were longer in duration (figure 8.0a) with an increased reliance on the deceleration (figure 8.0c) and final adjustment phases (figure 8.0d) coupled with more adjustments made in the approach (figure 8.1a) and final adjustment phase (figure 8.1b) when compared to unimanual movements. However, the difference between unimanual and bimanual conditions did not reach significance for the final adjustment phase despite more adjustments being made in the bimanual condition (unimanual=2.51, bimanual=4.68). Finally, for the grasp phase MGA (figure 8.2a) was larger and occurred earlier (figure 8.2b) in the bimanual condition when compared to the unimanual condition, in agreement with previous research (Marteniuk et al., 1984, Marteniuk et al., 1990).

Taken as a whole, these findings suggest that symmetrical bimanual movements come at a cost, e.g. prolonged movement time and earlier hand opening, but Jackson et al., (1999) postulated that this bimanual cost may be a strategy to maintain coordination between the limbs as the movement progresses. As this bimanual cost was evident in all participants within the study (even though there was no specific instructions to do so) it provides further support to findings of study two, in that despite injury to the cervical spinal cord the aim was to complete the bimanual movement in a coordinated fashion.

In the stroke literature, bimanual movements are shown to improve limb performance of the more impaired limb (e.g. increased movement time and increased peak velocity) when compared to unimanual conditions (Rose and Winstein, 2004, Rose and Winstein, 2005). However, in the current study there was no significant condition by limb interactions that emerged. The lack of significant main effect of limb for the kinematic and EMG dependent variables suggests that despite disparate abilities of the two limbs following icSCI, both limbs showed similar bimanual costs and therefore provides further evidence of bimanual coordination. This could be due to neural crosstalk between the two limbs as low level (via the CST) and high level (via the corpus callosum) crosstalk permits movement assimilation e.g. similar movement time, similar timing of peak muscle activity, between the two limbs (Marteniuk and MacKenzie, 1980).

Overall, as participants with an icSCI can still complete bimanual movements in a coordinated fashion with no specific training (conventional therapy is unimanual in nature) and in the acute stage of injury, this supports the inclusion of bimanual movements during rehabilitation to subsequently improve performance of activities of daily living, which are more often bimanual in nature. The acute stages of injury are known to induce the greatest neuroplasticity (Curt et al., 2008), thus incorporating bimanual therapy at this early stage may maximise the improvements seen in bimanual arm and hand function.

8.6 Conclusion

The comparison between unimanual and symmetrical bimanual conditions revealed that participants with an icSCI show a similar pattern to YA and OA when moving bimanually, e.g. prolonged movement time and earlier hand opening, which is thought to be a strategy to maintain synchrony between the limbs. Taken together with the finding that there was no significant main effect of limb for kinematic or EMG variables, this suggests that despite bilateral deficits following icSCI, the aim was still to complete the bimanual task with the limbs moving together in a coordinated fashion.

Overall, this provides further support (in combination with study two) that following icSCI there is an ability to retain a level of bimanual coordination, despite no form of bimanual therapy being received. As the participants with an icSCI were in the acute stages of injury, which is coupled with the greatest neuroplasticity (Curt et al., 2008), the integration of bimanual therapy into rehabilitation could drive further neuroplastic changes and lead to greater improvements in arm and hand function.

Chapter 9 General discussion

9.1 Introduction

Despite regaining upper limb function being of the upmost importance to individuals with a cervical spinal cord injury (Anderson, 2004, Snoek et al., 2004), the literature investigating how control of upper limb movement changes after cSCI is lacking when compared to other clinical populations (e.g. stroke) and focuses solely on unimanual prehension. However, as most activities of daily living require the use of both hands simultaneously, the emergence of support for the use bimanual therapy within the spinal cord injury literature is growing (Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2010, Hoffman and Field-Fote, 2013).

Despite initial evidence for the benefit of bimanual therapy, there has been no study to my knowledge that has investigated how bimanual control changes after injury to the cervical spinal cord, and subsequently what rehabilitation should aim to improve. Additionally, there has been little research based on upper limb control in the acute stages of injury to the cervical spinal cord and following incomplete SCI, although these are where the greatest functional gains and neuroplasticity (12-15 weeks post injury) are evident (Curt et al., 2008, Raineteau and Schwab, 2001). Finally, due to the aging population of those suffering from a SCI (Thompson et al., 2014), within this thesis it was important to consider how upper limb function differs to both younger and older non-injured participants. This gives insight into which changes in control are due to aging and which are due to injury to the cervical spinal cord.

The first study comprised two experiments (object distance and object size) which aimed to quantify how unimanual prehension changes after icSCI, and how this compared to non-injured younger and older adults. Study two, examined bimanual prehension following icSCI, and how this differed to non-injured YA and OA. Within this study, object distance and object size, were used to manipulate task symmetry. Finally, the third study aimed to compare the control of unimanual and bimanual movements following icSCI, and how this differed to non-injured YA and OA. Within the three studies in this thesis the following hypotheses were tested:

(1) Participants with an icSCI will display longer (duration), slower (lower peak velocity), less smooth (more adjustments) movements than non-injured participants.

(2) Participants with an icSCI will display novel muscle patterns (in terms of timing of peak muscle activity) when compared to non-injured control participants due to muscle paralysis.

(3) Object distance and object size will influence kinematic parameters such as movement time and timing of maximum grasp aperture formation.

(4) Participants with an icSCI will produce less synchronous movements than non-injured YA and OA due to declines in sensory and motor function.

(5) Bimanual movements will be longer and slower than unimanual movements for all participants.

9.2 Main findings and clinical implications

In agreement with the first hypothesis, the studies in this thesis found that participants with an icSCI produced movements of a longer duration and lower peak velocity than non-injured younger adults and older adults, with an increased reliance on the deceleration and final adjustment phase of the movement. This agrees with previous research in the unimanual prehension literature (Mateo et al., 2013, Hoffmann et al., 2006, Laffont et al., 2007, de los Reyes-Guzmán et al., 2010, Laffont et al., 2000, Mateo et al., 2015), and extends those findings to bimanual movements addressed during study two and three (chapter 7 and 8). This motor slowing (longer movement time, lower peak velocity) could have arisen due to one of two explanations. The first is that participants with an icSCI could have slowed their movements down in order to maintain accuracy as per Fitts law and the speed accuracy trade off (Fitts, 1954). The prolonged movement time would allow for accurate finger and thumb placement around the object before object pick up. The earlier hand opening seen throughout the three studies also supports the notion that participants with an icSCI aimed to maintain accuracy, as this control strategy allows for error correction in finger and thumb placement around the object.

The second possible explanation for motor slowing seen in participants with an icSCI, compared to non-injured YA and OA, could be due to paralysis of the triceps brachii and biceps brachii following cSCI preventing agonist-antagonist muscle activity, which acts to extend the elbow (triceps brachii) and then prevent further extension of the upper limb (biceps brachii, begins elbow flexion) in non-injured participants (Hughes et al., 2009, Koshland et al., 2005). Therefore the lower peak velocity and prolonged movement time may be a strategy used following icSCI to reduce the reliance on the triceps brachii and biceps brachii agonist-antagonist co-contraction synergy (Mateo et al., 2015), as faster movements require a greater braking force in order to slow the limb down (Hughes et al., 2009). This is supported by the EMG results within the present thesis (all studies) as agonist-antagonist muscle activity between the triceps brachii and biceps brachii was reduced in participants with an icSCI compared to non-injured participants. In order to apply a braking force to the upper limb participants with an icSCI showed the emergence of a novel muscle pattern (in agreement with hypothesis two) in that peak muscle activity occurred at the start of the final adjustment phase.

This novel muscle pattern could be explained by the well documented neuroplasticity that occurs after SCI, and while not directly tested the literature suggest that this neuroplasticity could reflect synaptic modifications or axonal sprouting of spared fibres of the CST (Raineteau and Schwab, 2001, Oudega and Perez, 2012). The changes in muscle activity pattern denotes motor redundancy after icSCI, which reflects the nervous system's ability to achieve a kinematic outcome (in this case the reach to grasp movement) using novel muscle patterns (Koshland et al., 2005). From a clinical perspective, improving muscle strength in the triceps brachii and biceps brachii could reduce this motor slowing by allowing a greater braking force to be applied by the biceps brachii in order to stop further extension of the elbow, as in non-injured individuals (Koshland et al., 2005, Hughes et al., 2009) . Evidence has suggested that bimanual therapy improves triceps brachii strength (identified using the manual muscle strength test) and reverses cortical reorganisation of the biceps brachii (enlargement, increase in cortical excitability and anterior shift of the motor map), which are both associated with improvements in upper limb function (Hoffman and Field-Fote, 2007). This therefore implies that the use of bimanual therapy could be beneficial following icSCI and reduce motor slowing over time.

The second main finding from the studies in this thesis relates to the increased proportion of movement time spent in the deceleration and final adjustment phase seen in participants with an icSCI (for both limbs) throughout all studies when compared to YA. The group difference between participants with an icSCI and OA did not reach significance in the bimanual conditions (study two and three), which suggests that both of these groups use the final adjustment phase for error correction when moving bimanually. The most likely explanation for these findings are the declines in the ability to process sensory feedback, and in particular the loss of proprioceptive feedback regarding limb position. This has already been supported during bimanual movements in older adults (Coats and Wann, 2012) as declines in proprioceptive abilities with age (Sosnoff and Newell, 2006) lead to an increased reliance on visual feedback to guide the movement. Visual feedback for error correction in limb position and successful finger and thumb placement around the object can only be obtained when the limb is close to the object, i.e. late in the movement, thus explaining the increased amount of time in the final adjustment phase. Additionally, during bimanual movements both limbs and objects cannot be visually fixated at once and require shifts in fixation, which increases the amount of time needed in the final adjustment phase in bimanual conditions. The role of visual feedback has also been supported in deafferented patients (loss of proprioception) during unimanual movements, which relates to the individuals with an icSCI as in combination with declines with age (participants with an icSCI were often older adults), the damage to afferent (sensory) fibres, e.g. in the CST (Lemon and Griffiths, 2005), resulted in significant differences to YA for propDT and propFAP in unimanual and bimanual movements.

The loss of synchrony between the two limbs when compared to YA and OA (evident in study two and in agreement with hypothesis four) provides further support for the use of visual feedback after icSCI, due to loss of proprioceptive abilities (Bruyn and Mason, 2009). This is because visual feedback naturally induces asynchrony between the two limbs as it not possible to fixate both limbs and objects at one time (Riek et al., 2003). The main effect of condition in experiment one (in study two, chapter 7, section 7.3.11) for participants with an icSCI also supports the reliance on visual feedback, as asymmetrical bimanual conditions have already been shown to induce more asynchrony between the limbs than symmetrical conditions in non-injured adults. This is because asymmetrical conditions impose the requirement to shift visual fixation from one hand/object to the other (Riek et al., 2003, Mason and Bruyn, 2009, Bingham et al., 2008). In order to provide further support for the role of visual feedback following icSCI more research should be undertaken to provide a full understanding e.g. how reach to grasp kinematics change when vision is reduced or eliminated.

From a clinical perspective integrating bimanual therapy with somatosensory stimulation (Hoffman and Field-Fote, 2010) or functional electrical stimulation (Hoffman and Field-Fote, 2013) has been shown to increase cortical motor excitability and improve sensory function following injury to the cervical spinal cord. This may subsequently reduce the reliance on visual feedback, as sensory feedback and proprioceptive abilities improve. Recently, evidence has suggested that short term (5 days) bihemispheric anodal corticomotor transcranial direct current stimulation (tDCS) (stimulation to activate the right and left corticomotor hand areas), induces improvements in bimanual hand function in non-injured individuals as it leads to increases in corticomotor excitability, that remains increased between use (Gomes-Osman and Field-Fote, 2013, Alonzo et al., 2012). This could be an emerging non-invasive modality to improve bimanual arm and hand function following icSCI in combination with physical bimanual therapy.

With regards to the grasp phase, participants with an icSCI were still able to scale their maximum grasp aperture to object size in agreement with previous unimanual research (Stahl et al., 2014). However, participants with an icSCI were shown to produce a larger MGA than YA (unimanual movement near/small object) and form MGA earlier in unimanual and bimanual movements than YA and OA, which could be a strategy to allow for error correction and accurate finger and thumb placement around the object (Marteniuk et al., 1990). Alternatively, damage to descending pathways, e.g. the CST, could have resulted in these changes in grasp formation, as unilateral transection of the CST (in primates) has been shown to cause deterioration in precision grip formation, namely by producing deficits in preshaping of the hand (Sasaki et al., 2004). Additionally, the direct CM networks of the CST (Bennett and Lemon, 1996) and premotor spinal interneurons (Takei and Seki, 2013) have been shown to influence grip force modulation and therefore participants with an icSCI (disruption of these pathways) may have spent an increased amount of time in the final adjustment phase to produce adequate grip force around the object. Aging has also shown to result in declines in grip force modulation (Voelcker-Rehage and Alberts, 2005), which is relevant to the population of participants with an icSCI in this study as they were often older adults. Future research should include the application of force transducers on the object surface in order to quantify how grip modulation influences the reach to grasp movement.

Object distance and object size influenced the transport and grasp kinematics during unimanual and bimanual movements (hypothesis three). In particular increasing object size posed greater task difficulty for participants with an icSCI as movements were longer in duration and resulted in a greater proportion of the movement being spent in the final adjustment phase when reaching for the large object compared to the small object. This may have occurred due to the reduced maximum grasp aperture previously reported following injury to the cervical spinal cord (10-11cm compared to 14cm in non-injured adults) (Stahl et al., 2014). The reduction in maximum grasp aperture reduces the safety margin (margin between MGA and object size) and may have resulted in more time being needed for successful finger and thumb placement around the object and prevention of object collision. Introducing higher levels of friction to the object surface has been shown to increase the effective zone for finger placement and therefore reduce the margin for error in older adults (Holt et al., 2013). Therefore future work in individuals with an icSCI could be focused on the effects of object texture (introducing low friction and high friction objects) on reach to grasp kinematics, to determine whether high friction surfaces aid the performance of the precision grip for large objects, and could have important ramifications for product design. As other areas of the body, such as the face, take over the cortical representation of the arm and hand in the somatosensory cortex (Jain et al., 1998) in a 'use or lose it' context (Field-Fote, 2009) (see chapter 1, section 1.5), increasing sensory input through the use of object texture (tactile sensation) may help to reverse cortical reorganisation after injury to the cervical spinal cord and increase the size of the motor map of the arm and hand.

Throughout study two and three the results indicated that despite bimanual deficits (paralysis of both upper limbs) following injury to the cervical spinal cord there is evidence for a level of bimanual coordination being retained. The first indication of this was that despite participants with an icSCI producing less synchronous movements than YA and OA, they showed evidence for aiming to complete the bimanual movements in a synchronous fashion by utilising the final adjustment phase to decrease the time difference between limbs at the end of the task, without specific instruction to do so.

The second finding indicative of bimanual coordination came from study three and the finding that participants with an icSCI showed similar patterns of bimanual cost to YA and OA when performing bimanual movements compared to unimanual movements. This bimanual cost (relating to hypothesis five) included prolonged movement time, increased reliance on the deceleration and final adjustment phases, larger and earlier MGA formation when completing bimanual movements, and agreed with findings in previous research in non-injured participants (Kelso et al., 1979, Jackson et al., 1999, Marteniuk et al., 1984, Marteniuk et al., 1990). Jackson et al., (1999) postulated that this occurred in order to maintain synchrony between the two limbs during bimanual movements in a study based on non-injured adults, and provides further evidence that participants with an icSCI aimed to complete the task in a coordinated fashion. Finally, the lack of significant main effect of limb for the kinematic and EMG dependent variables suggests that despite disparate abilities of the two limbs following icSCI, both limbs showed similar bimanual costs and therefore provides further evidence of bimanual coordination. This could be due to neural crosstalk between the two limbs as low level (via the

CST) and high level (via the corpus callosum) crosstalk permits movement assimilation e.g. similar timing of peak muscle activity between the two limbs (Marteniuk and MacKenzie, 1980).

Taken together these findings suggest that even without specific bimanual training individuals with an icSCI still show signs of bimanual coordination that could be improved by introducing bimanual movements into rehabilitation. Additionally, as the participants were in the acute stages of injury, incorporating bimanual therapy at this early stage will help to maximise neuroplasticity and improvements in function (Curt et al., 2008). In the emerging literature, bimanual therapy has already been shown to improve the performance of activities of daily living that are often bimanual in nature (e.g. fastening buttons or dialling a telephone), even after a short period of time (3 week interventions), and in participants that have sustained a complete cSCI (Hoffman and Field-Fote, 2007, Hoffman and Field-Fote, 2010, Hoffman and Field-Fote, 2013). Therefore the longer term inclusion of bimanual movements into therapy could improve functional independence and quality of life already known as a main priority for rehabilitation (Anderson, 2004, Snoek et al., 2004).

9.3 Potential limitations

Inherent in research and exploratory studies are the potential for limitations and with respect to this thesis the first limitation relates to participants with an icSCI. This is because the skeletal level and severity of the icSCI (ASIA B-D) varied between participants and therefore each participant had differing levels of upper limb paralysis. Having said this, the research fulfilled the aims and quantified unimanual and bimanual prehension after incomplete injury to the cervical spinal cord and therefore gives a general description of upper limb control. The inclusion of eighteen participants with an icSCI is also greater than previous research in which there are often less than ten participants, e.g. Mateo et al., 2013 recruited four participants with a C6 SCI and Stahl et al., 2014 recruited eight participants with a C5-C7 SCI. Additionally, the research was undertaken within two different Spinal Cord Injury Centres in the UK, which provided a wider cross section of participants for inclusion within the studies and representation of a wider UK SCI population.

Secondly, surface EMG recording comes with limitations e.g. muscular crosstalk and movement artefacts, which could both reduce the accuracy of the EMG recording. However, due care and attention was taken to ensure accurate electrode placement and the amplifiers and wires were taped down (to reduce movement artefacts) to ensure that the recordings taken were as accurate as possible. The

EMG system came under some technical difficulties regarding synchronisation with the kinematic system within the Spinal Injuries Centres, however, this was only the case for three of the eighteen participants enabling a good sample of data to be analysed.

Lastly, the inclusion of more extensive motor and sensory function tests, e.g. key pinch strength measurement via a digital handheld dynamometer and Semmes-Weinstein Monofilament test to measure limb sensation (Hoffman and Field-Fote, 2007), would have allowed a more extensive analysis of upper limb function. These two measures would have allowed for identification of deficits in grip strength, which may have influenced the ability to generate the precision grip and also identified the amount of decline in proprioceptive ability, which could have given a more definite explanation of findings in the thesis (e.g. increased reliance on the final adjustment phase). For the current thesis this was not possible due to time restrictions with each participant due to standard care protocols within the NHS. Future research, where possible, should aim to incorporate these types of measures to provide a more comprehensive understanding of upper limb function.

9.4 Summary of future directions

In this section the recommendations for future research that have arisen from the current thesis will be discussed. In general future work should aim to quantify sensorimotor deficits in more complex ways in order to develop the knowledge of control changes after injury to the cervical spinal cord.

Firstly, from the findings emerging in this thesis it would be interesting to examine the role of visual feedback on the control of unimanual and bimanual movements following icSCI. This is due to the increased reliance on the final adjustment phase and declines in synchrony between the limbs indicative of the importance of visual feedback. It could be done by manipulating the amount and/or timing of visual feedback available during and before the reach to grasp movements, which has already been done in older adults (Coats and Wann, 2011) and deafferented patients (Gordon et al., 1995). This data would give further detail regarding the planning and execution of movements and feedback control following icSCI.

Secondly, due to changes in kinematic parameters (e.g. longer movement time, increased propFAP, earlier hand opening) seen when reaching and grasping the large object in participants with an icSCI, it would be interesting to determine the influence of manipulating object texture. Previous research in older adults (Holt et al., 2013) has shown that increasing object friction on the object surface increases the effective zone for grasping and reduces the margin for error, which are both relevant to participants with an icSCI due to their reduced ability to maximally open the hand reported in previous literature (Stahl et al., 2014).

Thirdly, including measurements of grip force on the object surface would give further insight into grip force modulation after icSCI, which may show declines due to disruption of the CST and premotor spinal interneurons (Lemon et al., 1995, Takei and Seki, 2013), or natural aging declines (Voelcker-Rehage and Alberts, 2005).

Finally, the inclusion of more proximal and distal muscles within the EMG analysis, such as the pectoralis major, posterior deltoid and flexor/extensor carpi ulnaris, will help us to understand the biomechanical and physiological interactions pertaining novel muscle patterns following icSCI. This is because previous unimanual research has shown that participants with an icSCI rely more heavily on the shoulder complex to produce passive extension of the elbow (Koshland et al., 2005). Additionally, the bimanual connections (CST and Corpus Callosum) between distal muscles are less pronounced than proximal muscles (Brinkman and Kuypers, 1973, Donchin et al., 1999, Carson, 2005), therefore in bimanual movements differences in distal muscle activity between limbs may emerge.

9.5 Conclusions

This thesis highlights the difference in fine motor control between participants with an icSCI and non-injured younger and older adults. It also identifies when these differences are more apparent e.g. with increasing object size and in asymmetrical bimanual movements. The research has expanded the knowledge of upper limb control after injury to the cervical spinal cord and addressed the control of bimanual movements, which has not been published elsewhere in the SCI literature.

Overall, the findings suggest that participants with an icSCI display differences in kinematic and EMG control in the transport and grasp phases of unimanual and bimanual prehension when compared to younger and older adults. However, despite injury to the cervical spinal cord a level of bimanual coordination is retained. Taken together with the already established, albeit limited, evidence that bimanual therapy improves bimanual upper limb function and performance of activities of daily living, this research supports the inclusion of bimanual therapy within rehabilitation.

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List of Abbreviations

ADL	Activities of Daily Living
ASIA	American Spinal Injury Association
ANOVA	Analysis of Variance
CAHAI	Chedoke Arm and Hand Activity Inventory
cSCI	Cervical Spinal Cord Injury
CST	Corticospinal tract
CM	Corticomotoneuronal
EDS	Extensor Digitorum Superficialis
END	End of the movement
EMG	Electromyography
FAP	Final Adjustment Phase
FF	Preferred/Less Impaired limb and Non-preferred/More Impaired limb reaching for the far objects (condition two in experiment one of study two)
FN	Preferred/Less Impaired limb reaching for the far object and Non-preferred/More Impaired limb reaching for the near object (condition four in experiment one of study two)
iSCI	Incomplete Spinal Cord Injury
icSCI	Incomplete Cervical Spinal Cord Injury
LI	Less Impaired
LL	Preferred/Less Impaired limb and Non-preferred/More Impaired limb reaching for the large objects (condition two in experiment two of study two)

LS	Preferred/Less Impaired limb reaching for the large object and Non-preferred/More Impaired limb reaching for the small object (condition four in experiment two of study two)
MGA	Maximum Grasp Aperture
MI	More Impaired
MT	Movement Time
NF	Preferred/Less Impaired limb reaching for the near object and Non-preferred/More Impaired limb reaching for the far object (condition three in experiment one of study two)
NN	Preferred/Less Impaired limb and Non-preferred/More Impaired limb reaching for the near objects (condition one in experiment one of study two)
NOAA	Number of Adjustments in the Approach Phase
NOAF	Number of Adjustments in the Final Adjustment Phase
NP	Non-preferred
OA	Older Adults
P	Preferred
PV	Peak Velocity
PN	Propriospinal Neuron
propDT	Proportion of movement time spent decelerating
propFAP	Proportion of movement time spent in the final adjustment phase
RST	Reticulospinal Tract
SCI	Spinal Cord Injury
SS	Preferred/Less Impaired limb and Non-preferred/More Impaired limb reaching for the small objects (condition one in experiment two of study two)

SL	Preferred/Less Impaired limb reaching for the small object and the Non-preferred/More Impaired limb reaching for the large object (condition three in experiment two of study two)
ST	Start of the movement
TMS	Transcranial Magnetic Stimulation
TrG	Transport and Grasp Phase Coupling
YA	Younger Adults