Hand preference after stroke:

The development and initial evaluation of a new performance-based measure.

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Functional recovery of the upper limb after stroke is influenced by many factors, one being the amount of use of the affected arm and hand. In the healthy population, amount of hand use is influenced by degree of hand dominance. Depending on side of stroke and pre-morbid hand dominance, these preferences may be altered after stroke impacting on the amount of use. As a result it is important to be able to quantify the post-stroke arm preference since it could have important implications to recovery. Determining hand preference in patients after stroke is not commonly measured. When it is measured this is done using questionnaires which have limitations when applied to those who have had a stroke. A performance-based reaching task has been shown to correlate with the degree of hand dominance as determined by the Waterloo Handedness Questionnaire in healthy subjects. This tool provides an objective method to assess the continuum of hand dominance and may be a more appropriate method to evaluate hand preference after stroke. The purpose of this study was to develop and conduct initial tests on a modified version of this preferential reaching task, with varying degrees of proximal to distal control. The study investigated the influence of impairment; pre-stroke dominance and task difficulty on affected arm reach percentage.

Results of the study revealed that it is feasible to administer, in a clinical setting, a modified preferential reaching task in the stroke population, as the test could be completed in less than 10 minutes with no adverse effects reported from the patients. Heterogeneity made it difficult to detect statistical effects of task difficulty and pre-stroke dominance on post-stroke preference; however, there were trends observed indicating that patients with their dominant arm affected may have greater preference for the affected arm compared to those with their non-dominant arm affected. This difference in preference occurred despite similar impairment levels

between these patient groups. Preference for the dominant arm (whether affected or unaffected) was stronger when the task was at midline or in contralateral space, and when tasks required the greatest degree of distal control. In future, the degree of hand preference measured with such a performance-based tool may have important implications for identifying areas in therapy requiring greater focus as well as identifying individuals who would most benefit from therapies that promote affected arm use, such as constraint induced movement therapy.

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1. Introduction

Stroke is the leading cause of neurological disability in adults, costing an estimated $3.6 billion per year in medical care, lost wages and decreased productivity (Heart and Stroke Foundation Canada, 2000). In Canada, there are over 300,000 adults living with some form of disability as a result of stroke (Heart and Stroke Foundation Canada, 2009), with 80-90% of patients incurring acute hemiparesis of the contralesional upper limb (Hendricks et al., 2002). Despite rehabilitation efforts the upper extremity does not recover as well as the lower limbs (Nakayama, 1994), and 40% of patients suffer chronic impairment of their arm and hand (Heart and Stroke Foundation Canada, 1999). Predicting functional recovery in the upper limb is crucial to design cost effective, focused rehabilitation and ultimately improve quality of life following stroke.

Functional recovery of the upper limb after stroke is influenced by many factors, including lesion size and location, comorbidities, depression, cognitive deficits, and the amount and quality of paretic limb use (Krakauer, 2005). The latter is of particular interest as it has the potential to be greatly influenced after a stroke. Regardless of the amount of practice received in therapy it is crucial to use the paretic limb often in everyday activities in order to facilitate use-dependent changes in cortical representation, as observed in the outcomes of constraint induced movement therapies, which improve upper limb function by restraining the healthy arm for the majority of waking hours (Taub, 1993). However, one critical variable that can influence the effectiveness of such therapies is whether the affected hand was dominant or non-dominant prior to stroke (Waller and Whitall, 2005).

One of the most important determinants influencing amount of arm and hand use in healthy individuals in daily life is hand dominance, with 90% of people choosing their right for unimanual tasks (Annett, 1970; Bryden, 1977). There exists a unique challenge after stroke about the specific involvement of the right or left limbs depending on pre-stroke hand dominance. After having used one limb over the other for years, it is expected that this will have an impact on the motivation to use the affected limb. More specifically, there is evidence that whether the stroke involves the limb that was dominant prior to the stroke results in a lesser degree of impairment and greater gains in the affected limb in certain therapeutic programs (Harris and Eng, 2006). Importantly, task-specific hand preference likely changes following stroke based on the degree and side of paresis. There is limited data on the change in hand preference after stroke; however one study indicated a significant change in hand preference to the unaffected limb particularly if the subject suffered a stroke to their dominant cortex (Langan and van Donkelaar, 2008). In spite of the potential importance of hand preference on recovery there remains relatively little known about the characteristics of such hand preference and how this may change over the course of recovery. In addition, there is relatively little known about the relationship between pre-morbid hand dominance and post-stroke hand preference. Note that for the purposes of this thesis, the term limb *dominance* will be used to describe the limb used most frequently by the person prior to stroke. The term limb *preference* will refer to the limb used most frequently post-stroke.

Although the determinants of hand dominance are not entirely clear, it is postulated that a mix of genetic and environmental, or sociocultural, factors influence the asymmetries observed in the healthy population (Annett, 2002; Yeo et al., 2002). However, post-stroke hand preference is likely influenced by pre-stroke dominance, the characteristics of the post-stroke impairment (severity and side) and the tasks to be performed. The nature of this preference has important potential implications to recovery of function, based on the principles of usedependency, and ability to successfully perform activities of everyday life. Importantly, post-stroke hand preference may vary with recovery and may be an important functional index of changes after stroke.

In spite of the potential importance of hand preference, it is not commonly assessed clinically. When it is assessed it is most commonly done by self-reporting of the hand individuals prefer to use to perform specific tasks. For example, the revised Bryden Handedness questionnaire, requests self-reports related to the hand used for writing, throwing a ball, drawing, using scissors and brushing teeth (Bryden, 1977). There are significant limitations for using this approach after stroke including: 1) the inherent limitations of the use of self-reporting (including cognitive status and ability to distinguish pre and post-stroke preference) and 2) the focus on a limited number of tasks that may or may not be appropriate for specific individuals after they have had a stroke (e.g. the tasks may not have been performed due to motor challenge).

Questionnaires have also been commonly used to assess limb dominance in healthy populations. One example is the Waterloo Handedness Questionnaire (Steenhuis and Bryden, 1989). However, as with adapted stroke scales these rely on subjective reporting. A more direct way, which has been evaluated in healthy adults, is a performance-based measure of hand dominance. Importantly, limb preference is best described as a continuum rather than a dichotomy that is linked to task difficulty and the location in workspace (Bishop, 1998). As a result, task performance, determined by task complexity and location that requires use of a single upper limb, can serve as an action-based determination of limb preference. An example is the Preferential Reaching Task (Bryden, Roy and Mamolo, 2003), which has been shown to correlate with the degree of hand dominance as determined by the Waterloo Handedness Questionnaire (Mamolo et al., 2006). The tasks assess preference as the subject can spontaneously choose which arm to use, at the same time being a performance measure by using a quantitative measure of frequency of hand reaches (Mamolo et al., 2006). Such a performance-based instrument, appropriately adapted to assess limb preference after stroke, may provide valuable information about recovery or be predictive of recovery. As a result, the purpose of this work was to do some initial development and evaluation of a performance-based measure to assess degree of limb preference after stroke. Important to this study is the selection of task difficulty. If all of the tasks are too difficult to perform there is no ability of the instrument to evaluate the continuum of hand preference, which makes it less sensitive to changes in degree of hand preference throughout recovery. For patients with some motor capability, there are simpler tasks that can still be performed; therefore expanding the range of task difficulty will allow a full evaluation of degree of hand preference post-stroke.

The specific objectives of this study are to: 1) establish the influence of limb impairment (side and degree) and pre-stroke limb dominance on post-stroke limb preference, 2) observe the influence of task conditions on overall percentage of affected arm use, and 3) observe the relationship between the ability to perform specific tasks and the willingness to use the affected arm when provided the opportunity to select either arm. Long-term objectives of this research are to create a reliable and valid measurement of hand preference that can be used to track recovery of contralesional arm function over time. Long-term therapeutic objectives would be to identify areas requiring greater focus in therapy and identify individuals who would most benefit from therapies that promote spontaneous affected arm use, such as constraint induced movement therapy. Ultimately this research will aid in the understanding of factors contributing to recovery of upper limb function following stroke.

2. Review of Relevant Literature

2.1 Prevalence of stroke, frequency and recovery of upper limb dysfunction

Upper extremity hemiparesis is present in 80-90% of patients acutely following stroke (Hendricks et al., 2002: Bogousslavsky, 1988), and despite rehabilitation efforts only one third ever regain completely normal function of their arm and hand (Parker, 1986). Stroke patients value return of upper extremity function as a high priority in their recovery (Bohannaon, 1988), and the inability to do so can lead to depression and withdrawal (Sinyor, Amato and Kaloupek, 1986). Impairment of the upper limb limits the ability of patients to participate in activities of daily living (ADL) and consequently limits their independence (Nakayama, 1994). Damage to the neuroanatomic structures responsible for motor function results in a decrease in cortical representation for muscles of the arm and hand. This leads to muscle weakness and atrophy, (Bourbonnais and Vanden Noven, 1989), spasticity (O'Dwyer, Ada and Neilson, 1996), and atypical movement synergies (Twitchell, 1951; Brunnstromm, 1966). Impairments exhibited by muscular systems separate from the upper limb will also influence arm movements, as the postural control required to accomplish normal arm movements is diminished (Di Fabio, Badke and Duncan, 1986). Secondary to muscle impairments are motivation (Kaufman and Becker, 1986), shoulder pain (Roy, Sands and Hill, 1994) and neurobehavioural deficits, such as motor planning (Levin, 1996) which all adversely affect upper limb function.

As a result of these impairments, critical functional movements, such as reaching, show increased movement time, decreased peak velocity (Parker, Wade and Langton, 1986), incorrect timing of movement components (Archambault et al., 1999), increased variability in kinematic measurements (Cirstea, 2000), and loss of interjoint co-ordination (Levin, 1996) when compared to healthy individuals.

Recovery is highly variable between individuals (Bach-y-Rita, 1990), and while most recovery occurs within months following stroke, it is possible to see recovery later in chronic phases (Hendricks, 2002). Despite the high variability, it has been postulated by Twitchell (1955), that all patients will pass through a predictable, step-wise course, and although some may plateau at any one of these stages, no stages will be skipped. Brunnstrom (1966) developed six recovery stages, and it is these stages on which the Chedoke McMaster Assessment is based (Gowland, 1993). The profile as described by Twitchell and Brunstromm follows the basic pattern of proximal to distal recovery, emergence and then waning of spasticity, and emergence and waning of synergy patterns. It should be noted however, that actual recovery profiles of individual patients, is highly variable and may or may not follow through typical patterns or progress through these stages (e.g. not all individuals reveal the proximal to distal progression) (Hendricks et al., 2002; Stineman et al., 1997).

Proximal joints receive greater innervation from ipsilateral motor pathways, which can partially explain the earlier recovery of proximal movements, such as shoulder flexion, rather than hand movements such as wrist and finger flexion (Chen, 1997). However, recovery by ipsilateral motor pathways is not ideal, as MEPs from this pathway show a longer latency, lower amplitude and higher threshold, and it has been associated with poor motor outcome; therefore to achieve full recovery of function it is necessary to recruit the ipsilesional pathways in movement (Jang, 2007). There is also a pattern of flexion synergies to recover before extension synergies, and initially the ability to perform extension followed by flexion recovers before the opposite. This can in part be explained by primitive reflexes that are unmasked due to inhibition being removed as a result of higher level CNS damage. The propensity to keep the arm in a flexor state also leads to contractures in soft tissues on the flexor side of the joint causing a greater disparity between flexor and extensor musculature (Mathiowetz, 1994).

However, as patients undergo therapy and regain certain levels of function this does not necessarily translate into an improvement in their level of disability and handicap. Through studies using accelerometry and questionnaires examining ADLs, studies have shown that the amount of actual use is only weakly correlated with clinical measures of function, with the actual amount of use commonly being less than the patient is actually able to do (Andrews, 1979; Taub, Uswatte and Morris, 2003; Sterr, Freivogel and Schmalohr, 2002). This discrepancy is a current cause for much research, and can partially be explained by the learned non-use phenomenon. The following section addresses this important matter of use-dependent influences on recovery after stroke.

2.2 Importance of use in recovery of upper limb

2.2.1 Use-dependent plasticity

The neurophysiological mechanism behind the reorganization of motor representation is the phenomenon of neuroplasticity. Neuroplasticity is the result of injury or increased use (Woolf and Salter, 2000) and is defined as an enduring change in neuronal structure, function or chemical profile. Neuroplasticity can be spontaneous (the month following stroke) or as a result of intense repetition of specific movements, such as those done over and over in physiotherapy (Lundy-Ekman, 2007). Much of the evidence, discussed below, of neuroplastic change after lesions to the central nervous systems have been documented in animal studies (Nudo, Wise and Milliken, 1996).

The events that specifically follow a stroke are importantly linked to the time that has passed after the initial event. In the first month following a stroke, the environment in the periinfarct cortex is favourable to axonal sprouting, unlike the normal inhibitory conditions in the healthy brain (Carmichael et al., 2005). The ischemic attack causes an increase in growth-promoting proteins and a concomitant decrease in growth-inhibiting proteins, around the edges of and in the surrounding region of the lesion (Ng et al., 1988; Stroemer et al., 1995). The process of axonal growth starts between days 1 and 3 post-stroke, with sprouting occurring between 7 and 14 days. Finally, four-weeks after the lesion occurred new axonal connections can be detected (Dancause et al, 2005). Another mechanism behind neurogenesis is the migration of neuroblasts from the subventricular zone to the injury site. The cytokine erythropoietin (EPO) is released following the hypoxia caused by stroke. EPO facilitates the migration of neuroblasts to the lesion as well as promoting their differentiation (Wang et al, 2004). The functional recovery of patients is correlated with the amount of reorganization that occurs in this spontaneous recovery, both in the perilesional area and the areas connecting to it (Ward and Cohen, 2004).

The neurobiological explanation for reorganization as a result of therapy is not entirely clear, as there are different ways for plasticity to occur. There could be alternate paths formed due to the redundancy in motor areas. Many muscles have multiple representations allowing the undamaged areas to compensate for the lesioned areas. “Unmasking” of silent synapses, increased efficiency of existing synapses and creation of new synapses can also occur with repeated stimulation. The mechanisms for these forms of long-term potentiation are described below. The intense repetition of specific exercises causes neurons to repeatedly fire action potentials on each other in order to produce these movements (Lundy-Ekman, 2007). When action potentials are fired, glutamate is released from the pre-synaptic membrane and binds to the NMDA (N-methyl-D-aspartate) receptor on dendrites of the post-synaptic neuron. This promotes calcium release in the post-synaptic cell. The calcium release causes phosphorylation and consequently insertion of glutamate AMPA receptors on the post-synaptic neuron. This switches a silent synapse into an active synapse, known as "unmasking." With continuous stimulation, repeated calcium release can trigger changes in genetic expression leading to synthesis of new proteins resulting in stronger and more synaptic connections. Genetic changes leading to a shorter and thicker dendritic spine would result in stronger synaptic connections and more synaptic connections means an increase in the number of spines on the post-synaptic dendrite. These changes result in a more efficient synaptic connection, translating to an increased excitability between neurons (Lundy-Ekman, 2007). These plastic changes can then be detected with TMS. The increase in synaptic efficiency can be seen with the larger MEP amplitude, and the increase in cortical representation reflects unmasking as well as axonal growth. The increase in cortical representation is not only highly correlated with the amount of recovery it is also task-specific (Bayona et al., 2005). A muscle has to be used in intense repetition of a skilled task in order to observe these cortical changes (Classen et al., 1998). This highlights the importance of the volume of use required to affect changes in the affected upper-limb making it crucial to use the affected limb in activities of daily living and not solely in therapy.

2.2.2 Training: Therapy as a use-dependent model for recovery

Functional recovery as a result of activity based rehabilitation after stroke provides key evidence for use-dependent plasticity (Hallett, 2001; Ziemann et al., 2001). The amount of functional improvement relies on the amount of practice, and the gains are only specific to the task that is trained (Carr and Shepherd, 1998; Levy et al, 2001; Liepert et al, 2000; 1998; Schaechter, 2004). Generalization and retention can be improved by varying task demands slightly, or by practising tasks in random order (Hanlon, 1996; Winnstein, Wing and Whitall, 2003). Recent studies have shown that the cortical reorganization seen in animals as a result of therapy is also exhibited in humans (Boroojerdi et al., 2001; Classen et al., 1998; Cramer and Bastings, 2000; Frost et al., 2003; Hallett, 2001; Liepert et al., 2004; You et al., 2005).

Constraint-induced movement therapy (CIMT) (Taub, 1993), is one such example of use-dependent plasticity. CIMT involves the patient wearing a mitt on their non-paretic hand, while they undergo intense physiotherapy for 6 hours a day, 5 days a week for 2 weeks. During therapy they would use the affected limb in behaviourally relevant motor tasks, always at the upper limit of their capabilities but not beyond, so as to avoid frustration. This technique is known as scaling, and the difficulty is gradually increased as the patient improves. As well, the patient wears the mitt for 90% of waking hours while at home, as long as it is safe to do so. This allows everyday tasks to be practised with the affected limb alone, while the non-affected limb plays a transport and support role in bimanual movements (Taub, 1993).

After two weeks of CIMT, the motor map of muscles in the hand as well as the MEP amplitudes significantly increase compared to pre-treatment and control groups (who underwent traditional therapy). These outcomes are reflective of increased excitability in the motor cortex and are correlated with the amount of functional improvement, as measured by self-report and objective measures (Kopp et al., 1999; Kunkel et al., 1999; Liepert et al, 2000; Sterr et al., 2002; Taub and Wolf, 1997; Wolf et al, 2006).

However, CIMT has many limitations in its application to the entire stroke population; as only 20-25% of patients meet the inclusion criteria (Wolf et al., 2005). In order to be eligible, patients must have a minimum of 10 degrees of wrist extension, which excludes many patients who could potentially benefit from increasing paretic limb use. As well, CIMT is not a practical long-term method as the mitt may interfere with everyday activities, thus decreasing the long-term compliance. This treatment also does not foster relearning of many bimanual tasks, which are also crucial to relearn in the process of recovery. Further, forcing the user to use their affected limb may not encourage the spontaneous use of the affected limb once the mitt is removed. It would be beneficial therefore to utilize the concepts behind CIMT to encourage use of the affected limb frequently in activities of daily living.

2.3 Importance of hand dominance and side of lesion on recovery of function

2.3.1 Recovery of those whose lesion affects dominant vs. non-dominant

A limited number of studies have examined the effect of hand preference and its impact on recovery of hand and arm function after stroke. One study, by McCombe and Whitall (2005) revealed a greater response to bilateral training when the affected side was dominant prior to stroke. Another study revealed better grip strength and tone when the affected limb was the preferred limb, which could be explained by a superior pre-morbid neuromuscular condition (Harris and Eng, 2006). Self-report measures have indicated no difference in amount of use of the affected arm between patients whether it was their dominant or non-dominant arm pre-stroke (Harris and Eng, 2006). This could be indicative of low sensitivity of subjective measures to accurately report amount of hand use in everyday life. A study by Rinehart et al. (2009), used a quantitative measure to evaluate amount of arm use in simulated activities of daily living. They found that when the dominant arm was affected the participants performed a greater number of bilateral tasks, compared to those with the non-dominant hand affected. This resulted in the dominant affected patients using their unaffected arm twice as much as the affected arm, whereas non-dominant affected patients used their unaffected arm 4 times as much as their affected arm. Severe limitations exist in all of these studies, as they only included small sample sizes and patients with mild impairments. Therefore, further investigation into the effect of previous hand dominance on functional recovery in a wider range of stroke survivors is warranted.

2.4 Biology of manual asymmetries as evidence of hand dominance

2.4.1 Central substrates

In addition to the behavioural asymmetries accompanying handedness, there exist asymmetries at a neurobiological level. Neuroimaging studies have revealed a correlation between the volume of gray matter in the central sulcus and performance of the contralateral hand in tapping rate (Herve et al., 2005). The amount of cortical representation in the somatosensory (Soros et al., 1999) and primary motor cortices (Volkmann et al., 1998) is also greater in the dominant hemisphere. Further, a study by Dassonville (1997) showed that the volume of activation observed in contralateral motor cortex in response to functional movements of the dominant hand was related to the degree of hand dominance, further supporting the theory for a continuum of hand dominance (Dassonville, 1997).

Differences are not only observed in the dominant cortex while performing goal-directed movements (as opposed to meaningless actions), research has also proven that the dominant cortex is more active while observing actions. Neural coupling exists between regions of action production and action observation, activating neurons in the ventral premotor and inferior parietal cortices (Rizzolatti et al., 2001; Binkofski and Buccino, 2006). This asymmetry may prove advantageous in relearning motor skills, as it has been observed that mental practice enhances motor skill acquisition. Therefore the greater ability to interpret action observation as the patient watches their healthy limb or a therapist perform the movements, may translate into greater functional gains when the dominant limb was affected.

2.4.2 Peripheral substrates

Continuous practice and use of the dominant side in healthy individuals creates a larger number of fatigue resistant, low threshold muscle fibres (Fugl-Meyer et al., 1982). Examination of muscle fibre composition has revealed a greater number of low-threshold, fatigue resistant muscle fibres in the FDI (first dorsal interosseous), (De Luca, Sabbahi, and Roy, 1986) and trapezius muscles (Farina et al., 2003) of the dominant side. Following stroke there is a selective loss of high threshold, large motor units which could have less of an effect on the dominant side, where there are a greater number of low threshold motor units (Lukacs, Vecsei, and Beniczky, 2008).

2.4.3 Evidence of change in hand preference after stroke

Few studies have explicitly quantified the change in hand preference after stroke; with one exception being Langan and van Donkelaar (2008), who investigated pre and post-stroke hand dominance using the Edinburgh Handedness Inventory (Oldfield, 1971). This questionnaire asks the participant which hand they use for 10 tasks including writing, throwing a ball, and sweeping. Participants can also indicate if they use each hand equally for each activity or one hand exclusively (Oldfield, 1971). Langan and van Donkelaar (2008) found a significant change in the degree of hand preference if the affected hand was dominant prior to stroke, and no change if the affected hand was non-dominant prior to stroke.

2.5 Measuring hand dominance (pre-stroke) and hand preference (post-stroke)

2.5.1 Healthy individuals

There exist numerous questionnaire forms used to assess handedness, including Annett (Annett, 1970), Bryden Revised (Bryden, 1977), Edinburgh (Oldfield, 1970) and Waterloo Handedness Questionnaires (WHQ) (Steenhuis and Bryden, 1989). The WHQ and Bryden questionnaires ask whether the person uses their left or right hand always (95% of the time), usually (75% of the time) or both equally for a variety of tasks ranging from picking up objects of differing sizes to manipulation tasks of varying difficulty. Points are allotted for each answer: 2 for 95% of the time, 1 for 75% of the time and 0 for equally. Negative values indicate answers in favour of the left hand, and positive the right hand. The greater the absolute score, the stronger the degree of hand dominance. All of the above-mentioned questionnaires show the general trend of increasing reliance on the dominant hand as the task difficulty increases (Annet, 1970; Bryden, 1977; Oldfield, 1970; Steenhuis & Bryden, 1989). Despite their potential to provide detailed information, as with all subjective measures, they rely on participant recall and memory, as well each person may construe the question meanings differently. Other limitations of questionnaires include the equal weight given to all tasks, and the cultural pressures on some items, especially handwriting (Calvert and Bishop, 1998).

An alternative to questionnaires, performance-based measures have been developed to assess degree of hand dominance in healthy individuals. One of the first was the Quantification of Hand Preference, which required participants to reach and pick up cards arranged at 7 positions across working space (Bishop et al., 1996). As in all performance-based tests of hand preference, the participants were not instructed which hand to reach with, and the hand chosen at each place was recorded. Extensive validation has been performed on this hand preference measure, showing that participants show a fairly constant pattern of reaching, and the tool can reliably separate participants in groups based on degree of hand dominance. Stins, Kadar and Costal (2001), varied task demands by having participants lift and replace a glass that was either empty or full of water. They found that dominant hand use was greater when task accuracy was increased (full glass). As well, the degree of hand dominance, as assessed by the Annett (1970) hand preference questionnaire, was positively correlated with the number of reaches made by the dominant hand. These performance-based measures varied task conditions by manipulating position and accuracy; however, there was no tool use involved, resulting in a range of only unskilled movements. Pointing and picking up tools is classified as an 'unskilled' action, and is not a highly lateralized response on questionnaires (Steenhuis and Bryden, 1989). In contrast, using tools requires greater precision and motor coordination and is usually preferentially performed by one hand over the other. Bryden, Roy and Mamolo (2003) created a preferential reaching task that required participants to point, pick up, or use various tools. The results indicated that reaches were always made in ipsilateral space by the dominant hand and as the level of skill requirements increased the dominant hand made a greater number of reaches, and reached further into contralateral space.

2.5.2 Post stroke

Currently, there is no generally accepted method to determine hand preference following stroke, with techniques ranging from asking which hand is used for writing to using Questionnaires designed for the healthy population, such as the Edinburgh Handedness Inventory (Oldfield, 1970). Evaluating hand preference after stroke introduces an added level of complexity as many patients may not yet have attempted all of the tasks on the questionnaires with their affected hand. As well, despite having a certain level of motor control, the range of task difficulty on the questionnaires may be beyond their current motor capabilities. Approximately half of all patients will have their dominant hand affected, which Langan and van Donkelaar (2008), showed caused a significant change in the degree of hand preference, assessed using the Edinburgh Handedness Inventory (Oldfield, 1970). Depending on time post-stroke, this may be a relatively new change to the patient, making it difficult to accurately quantify their post-stroke state of preferences with a questionnaire. Similarly, as the patient recovers function of their affected limb, their degree of hand preference may be changing as well, making it almost impossible to accurately self-report their current state of preference. Cognitive deficits may also be present, further inhibiting this process. Given the limitations of using questionnaires to assess hand preference after stroke, an objective measure that included tasks with a suitable range of difficulty would be ideal.

3. Rationale and Hypotheses

3.1 Rationale

An objective, performance based measure is desired to evaluate the degree of hand preference following stroke. A preferential reaching task correlates highly with the degree of hand dominance as determined by the Waterloo Handedness Questionnaire (Bryden, Pryde and Roy, 2000), providing an objective performance-based method to assess degree of hand dominance in healthy participants. However, the length of the current test takes a minimum of thirty minutes, making the test too lengthy to be realistically included as part of a standard clinical battery. Therefore to be included in a typical test battery without causing further fatigue to the patients, the ideal test would take less than 10 minutes, and require a minimal amount of equipment to be placed on the subjects.

The placement of objects for this test was modeled after that of Bryden, Pryde and Roy (2000); however, the tasks were modified to target the proximal to distal recovery profile of a stroke patient. Reaching was chosen as the primary task as this movement is critical to all parts of daily life such as grooming, toileting, feeding, transfers and dressing (McCrae, 2002). As the test progressed, task difficulty was increased by manipulating the following movement requirements: 1) accuracy of trajectory control, 2) force control when gripping and releasing and 3) demand for fractionated finger control.

The main objective of study 1 was to determine if the layout and tasks chosen could distinguish differences in post-stroke hand preference between patients with varying degrees of impairment as well as between patients who had their dominant or non-dominant arm affected. As well, it was important to determine the feasibility of conducting the protocol within the time constraints of a standard clinical assessment.

The results of study 1 revealed that the test was capable of discerning differences in patients with their dominant or non-dominant arm affected, and that this could be done within the time constraints. The results revealed a discrepancy between motor capacity in the affected arm and voluntary use of the affected arm. Except for 2 self-proclaimed 'ambidextrous' patients, the remainder of the patients with their non-dominant arm affected did not perform any voluntary reaches with their affected arm, despite all having the ability to complete the tasks. In contrast, the dominant affected patients performed numerous tasks with their affected arm despite having equal or lesser Chedoke McMaster Stroke Assessment (CMSA) scores than the non-dominant affected patients.

To reduce the floor effects observed in the patients with their non-dominant arm affected, the layout of task locations was rearranged. After observing patients attempting to reach targets closest to the affected side, it was discovered that these were the most difficult to reach with the affected arm. If this motion is analyzed it shows that there is greater inter-limb co-ordination and more complicated movement synergies required to reach sideways than is required to reach straight ahead. Shoulder abduction and external rotation is required to initiate a sideways reach, followed by shoulder flexion and elbow extension to complete the reach. Interjoint co-ordination is impaired following stroke (Levin, 1996), and the ability to perform shoulder abduction is not present until CMSA Stage 5. However, a straight ahead reach has fewer degrees of freedom (less interjoint co-ordination) and will require mainly shoulder flexion and elbow extension, which are muscle synergies elicited one stage earlier. Therefore, it was presumed that making the closest target a straight ahead reach would encourage more frequent use of the affected arm. This was accomplished by arranging all targets in a straight line parallel to the front edge of the table (Figure 2).

Another issue with study 1 concerned the ability of patients to choose the starting location of their hands. In the first study the hands were placed on the table at a location equidistant from all targets; however, the tendency of the patients was to angle each hand toward the contralateral targets. This was especially evident in the non-dominant affected group as they would angle the dominant, unaffected arm towards the workspace of the affected side, making it even more difficult to initiate an affected arm reach. This may also have contributed to the lack of use of the affected arm in this group. Based on these observations, arm supports were added in study 2 under each forearm, which resulted in both hands aiming forward toward the targets in ipsilateral space. The addition of arm support also allowed for inclusion of patients with greater muscle weakness, as they were not required to lift their arm to reach the target. In future, this would allow the same measurement tool to be used for a wider range of patient abilities, providing a more continuous measure that can be applied throughout the course of recovery.

3.2 Overall Hypotheses for Study 1 and 2

1A: As impairment increases, measured as the average arm and hand scores on the Chedoke McMaster Stroke Assessment, affected arm reach percentage will decrease.

1B: Patients with their dominant arm affected will have a higher overall reach percentage than those with their non-dominant arm affected.

2: As task difficulty increases, by challenging the control requirements of the distal segments (hand and fingers), the affected arm reach percentage will decrease.

4. Methods – Study 1

4.1 Subjects

For study 1, data was collected from 8 stroke patients (4 men and 4 women; age 60.9+/- 12.0y) Time since stroke ranged from 48 days to 24 months (mean 8 +/- 4months), CMSA arm scores ranged from 3-7 (mean 5.0 +/- 2.0), and hand scores from 2-7 (mean 5.9 +/- 1.6). Inclusion criteria were that they had suffered a stroke and scored a minimum of 2 for the arm component on the CMSA, indicating they were capable of some voluntary upper-limb movement. There were minimal exclusion criteria, as the objective of the study was to evaluate the usefulness of the tool on a wide range of stroke patients, including severity, time since stroke and pre-stroke dominance. Therefore the only exclusion criterion was the inability to understand and follow simple two-step commands (i.e. presence of receptive aphasia). In addition, 10 neurologically healthy control participants were recruited from the University of Waterloo (5 men and 5 women; age 22+/- 1.9y). This project received ethics approval through the TRI-Hospital Research Ethics Board and the University of Waterloo, Office of Research Ethics. All subjects provided informed written consent.

4.2 Clinical Measures

Stroke subjects were evaluated by a physiotherapist to assess severity of upper-limb impairment using the CMSA. Scores for arm and hand function were used, with a maximum score of 7 indicating “normal” arm function. A score of 1indicated flaccid paralysis, 2 and 3 severe motor deficit, 4 and 5 moderate motor deficit, and 6 a mild motor deficit. CMSA scores also provide an index for shoulder pain, with a maximum score of 7 indicating complete absence of shoulder pain and all prognostic indicators. Prognostic indicators include: arm stage 1 or 2, malaligned scapula, or diminished range of motion in the shoulder. Scores of 1 and 2 indicate constant (1) and intermittent (2) severe pain in more than just the shoulder. Scores of 3 and 4 indicate constant (3) and intermittent (4) pain in just the shoulder, and a score of 5 indicates pain is noted but does not interfere with daily activities. Scores of 6 and 7 indicate no shoulder pain; however, at least one prognostic indicator is present in stage 6 (Gowland et al., 1993).

4.3 Questionnaires:

All participants completed the Waterloo Handedness Questionnaire (Steenhuis and Bryden, 1989), and the Revised Bryden Handedness Questionnaire (Bryden, 1977), with the stroke patients providing both pre and post-stroke values.

4.4 Experimental Setup and Tasks

Reaches were made to a cylinder (diameter 6 cm; height 16.5cm), oriented with the long axis perpendicular to the table surface. The cylinder contains a strong magnet in one end; when the magnet side is against the table (on a ferrous insert), it provides the fixed condition, and is simply flipped over to provide the free condition, where it can fall over if contacted with too much force by the hand. The 'fixed' target cylinder allows the patient to make reaches requiring less accuracy and force control compared to the 'free' target cylinder. As the test progressed the task difficulty was increased by requiring the subject to reach and grasp the target cylinder. The fixed reach to grasp task provides a simpler degree of freedom as there is less finger extension required to release the cylinder, and again less force control required to complete the movement successfully. Adding in the free component to the reach to grasp movement required the patient to extend the fingers upon release to avoid knocking over the object. Finally, the last movement required the greatest amount of distal control as they had to use fractionated finger motion to pick up and place a small object (dime).

Participants were seated in front of the reaching table and placed their hands at the starting position shown in Figure 1, allowing an equal distance of 30 cm from the hands at each of the 7 target positions. Their hands were in a neutral position, halfway between supination and pronation with fingers in slight flexion, resting comfortably on the table. The five tasks were to be performed in sequential order, tasks were demonstrated by the experimenter and the following instructions given (ordered below on task difficulty, from low to high):

Task 1 - Reach and contact the fixed cylinder with the hand at a specified position (1 of 7), and return arm and hand to the starting position.

Task 2 - Reach and contact the unfixed cylinder at a specified position, without causing it to fall over, and return to starting position.

Task 3 - Reach, grasp and release the fixed cylinder, and return to starting position.

Task 4 - Reach, grasp and release the free cylinder, return to starting position. As in condition 2, the cylinder must not tip over.

Task 5 - Reach to specified position, pick up a dime and place onto the target location.

Control subjects completed 5 blocks of each task, with one block consisting of one repetition of each task randomly at all seven positions. For the stroke subjects the procedure was modified, with a maximum of 3 blocks for each task. The tasks, rated with 1 as the easiest and 5 as the hardest were performed sequentially and not randomly to minimize confusion and ensure the correct movement was performed by the participants. No instructions were given to indicate which hand to use, rather the participant was simply instructed to perform the task accurately, with no emphasis on speed, as would be typical in their everyday life. To maximize efficiency of time, if the participants performed identical reaching patterns (same hand used at each position) on two consecutive blocks of the same task, the next most difficult task would be attempted. Otherwise, a maximum of 3 blocks at each task would be performed. If no reaches were made by the paretic arm at a given task, then following completion of all blocks, the participant was asked to attempt to perform all of the tasks starting with task 1 until they could not successfully complete the next most difficult task. When performing in this "forced" condition, the participant was only required to reach to the middle position.

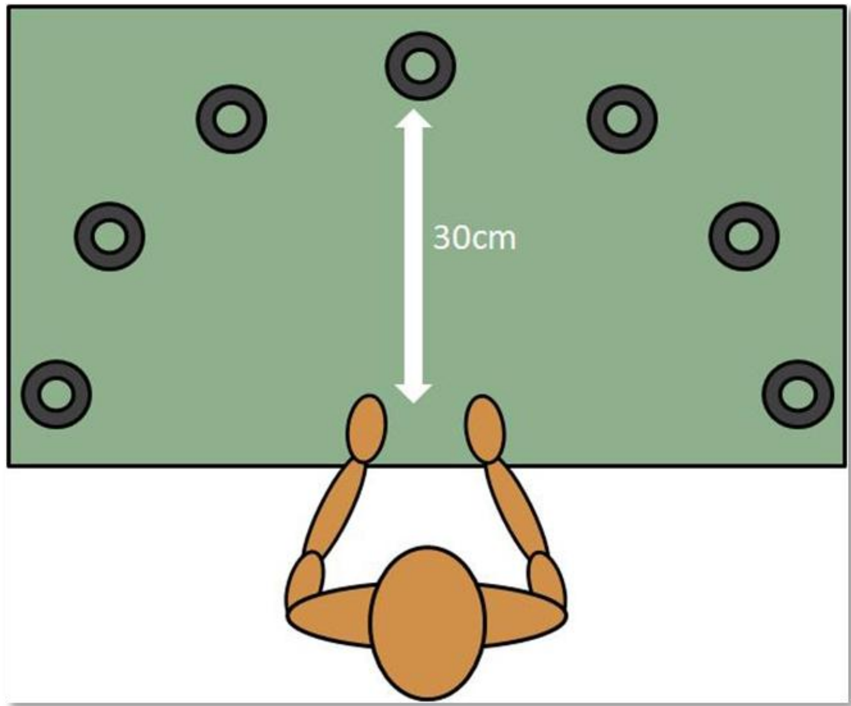


Figure 1: Schematics of experimental set-up for study 1. Patient sits at reaching table with hands resting on table. All task locations (black circles) are positioned 30 cm from starting location.

5. Methods – Study 2

5.1 Subjects

For study 2, data was collected from 13 stroke patients (4 men and 4 women; age 60.2+/-12.2y) Time since stroke ranged from 25 days to12 months, CMSA arm scores ranged from 2-7 (mean 5.4+/-1.9), and hand scores from 2-7 (mean 5+/-1). Inclusion and exclusion criteria were the same as study 1. In addition, 10 neurologically healthy control participants were recruited from the University of Waterloo (5 men and 5 women; age 25.2 +/- 2.0 years). This project received ethics approval through the TRI-Hospital Research Ethics Board and the University of Waterloo, Office of Research Ethics. All subjects provided informed written consent.

5.2 Clinical Measures

CMSA scores for arm, hand and shoulder pain were obtained as described in study 1. In addition, upper-limb motor ataxia, which indicates lack of coordination not explained by muscle weakness (Kasner, 2006), was assessed by a physiotherapist as part of the National Institute of Health Stroke Scale. Muscle tone of the elbow and wrist flexors was also measured by a physiotherapist using the Modified Ashworth Scale, where a score of 0 indicates no increase in muscle tone, 1 and 1+ are slight increases, 2 and 3 more considerable increases and a score of 4 indicates the body part is rigid in flexion or extension (Gregson et al., 1999). A trained research assistant evaluated strength and sensation; a dynamometer was used for pinch and grip strength, and von Frey filaments for sensation detection threshold. A summary of these clinical measures can be seen below in Table 1.

Table 1: Patient demographics and clinical scores. Ataxia scores, indicating lack of coordination, are for the upper limb (UL) or lower limb (LL), and MT represents muscle tone as scored on the Modified Ashworth Scale.

Patient	Age	Time Since (Mo)	Affected Side	Pre-stroke Dom	CMSA Scores			Grip Strength (kg)		Pinch Strength (kg)		Other
					Arm	Hand	Shoulder Pain	Affected	Unaffected	Affected	Unaffected	
1	78	1	Right	Right	2	2	6	4.3	45.7	0	7.8	Mild Sensory Loss
2	53	2	Left	Right	3	2	4	2	35.3	0	7.7	MT: Elbow 1, Wrist 2
3	50	6	Left	Right	4	2	6	2	18	0.1	5.3	Mild Sensory Loss
4	54	12	Right	Right	4	5	4	18.7	54.7	4.5	9.5	MT: Wrist 1 Ataxia: UL, LL
5	50	12	Left	Right	5	5	7	35.7	47	5.9	6.4	MT: Elbow, Wrist 1 Ataxia: UL, LL
6	69	6	Left	Right	5	5	5	15.7	32.7	2.8	4.1	none
7	43	6	Right	Right	4	5	6	8.2	21.5	1.7	3.5	MT: Elbow 1, Wrist 1+ Ataxia: UL
8	87	5	Right	Right	4	5	6	0	10	0	2.5	MT: Wrist 1
9	56	1	Right	Right	5	5	6	10	29.3	1.5	4.1	MT: Elbow 1, Wrist 1
10	60	12	Right	Left	6	7	4	23	38.7	3.7	6.7	Ataxia: UL (mild)
11	65	11	Left	Right	6	7	6	18.7	24.7	3.2	4.2	Mild Sensory Loss
12	54	12	Left	Right	6	7	7	39	40	7.8	8.3	none
13	64	2.5	Right	Right	6	6	4	6.7	12	2.2	3.5	none

5.3 Questionnaires

All participants completed the Waterloo Handedness Questionnaire (Steenhuis and Bryden, 1989), and the Revised Bryden Handedness Questionnaire (Bryden, 1977), with the stroke patients providing both pre and post-stroke values. Patients also completed the Stroke Impact Scale, specifically their self-rated ability to complete 5 functional activities with the affected arm and self-rated arm and grip strength of the affected arm (Duncan et al., 1999) (Table 2).

Table 2: Patient questionnaire responses indicating pre and post-stroke degree of handedness on the Bryden Revised and Waterloo Handedness Questionnaire (WHQ). Scores for the Stroke Impact Scale (SIS) indicate the patients' self-rated ability to complete the functional activities listed, and self-rated pinch/grip strength.

Patient	Handedness				SIS Tasks				SIS Strength	
	Bryden Pre	Bryden Post	WHQ Pre	WHQ Post	Turn Doorknob	Open Can	Tie Shoe	Pick up Dime	Arm	Grip
1	10	-10	28	-30	n/a**	n/a	n/a	n/a	n/a	n/a
2	10	10	24	30	n/a**	n/a	n/a	n/a	n/a	n/a
3	10	10	21	22	3	3	3	4	3	2
4	10	9	30	23	3	2	5	3	2	3
5	n/c	7	n/c	25	3	3	3	3	3	3
6	10	8	21	17	5	5	5	5	5	4
7	7	-5	20	-10	3	3	3	4	3	2
8	8	2	24	3	2	1	1	2	3	3
9	10	8	18	28	n/a**	n/a	n/a	n/a	n/a	n/a
10	n/c	-6	n/c	-12	2	3	3	3	3	3
11	n/c	10	n/c	26	5*	3*	3*	4*	3*	4*
12	n/c	10	n/c	20	5	5	5	5	3	3
13	10	10	19	24	n/a**	n/a	n/a	n/a	n/a	n/a

*completed on previous visit (same CMSA values)

** insufficient time post-stroke to complete SIS

5.4 Experimental Setup and Tasks

The revised reaching table was composed of ferrous metal with arm supports added, where the patients could rest between reaches (Figure 2). These supports were removable, which would allow for increasing difficulty in the future; however, for consistency they were used for all patients in study 2. There was 30 cm from the farthest point of the patients' hands to the location of the target that was straight ahead, other targets were further from each arm, and the midline target was equidistant from both arms. G-Link Wireless Accelerometer Nodes (MicroStrain Inc., Williston VT), sampling at 64 Hz, were strapped to the wrists of the participants, as well as attached with double-sided tape on posterior of the trunk, over the T1 vertebra. Another accelerometer was built into the cylinder to detect object movement, including contact time.

Patients were seated in a comfortable chair at the reaching table. The table was adjusted for height to create a 90 degree angle at the elbows when the forearms were resting on the arm supports. As well, the arm supports were adjusted horizontally to allow the elbows to rest in line with the shoulder joint. Aside from the setup of the reaching table, the rest of the procedure was the same as in study 1.

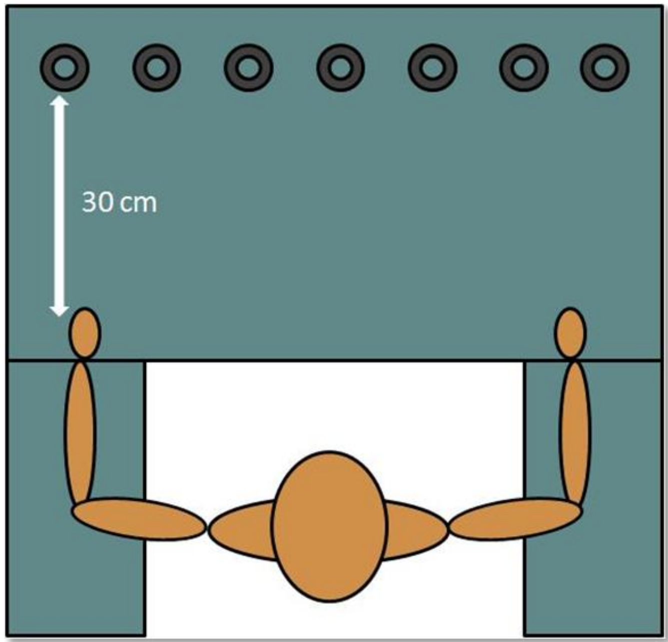


Figure 2: Schematics of revised experimental set-up for study 2. Patient sits at the reaching table with forearms resting on arm supports and hands directed forward. Task location (black circle) directly ahead in ipsilateral space are 30cm, midline task location is equidistant from both hands.

5.5 Statistical Analysis

5.5.1 Behavioural Measures:

The hand chosen to reach and complete each task, at each location was recorded to calculate the percentage of affected arm reaches. To examine the relationship between impairment and affected arm use, Spearman Rank Correlation was performed between average arm and hand scores for the CMSA, and the overall affected arm reach percentage. A Mann-Whitney *U* test was performed to determine if the overall reach percentage for patients with their dominant arm affected was significantly greater than patients with their non-dominant arm affected. Reach percentage between the handedness groups was further analysed based on those made to midline, ipsilateral and contralateral space (with respect to the affected arm). Two-way mixed ANOVA was performed to determine the main and interaction effects of task difficulty and pre-stroke dominance on affected arm reach percentage. Post-hoc Tukey's test was used to further examine any significant effects.

5.5.2 Kinematic Measures:

Accelerometers provided movement time from initiation of movement to object contact (movement time one), and movement time of manipulation back to starting position (movement time two). A customized program in Labview (National Instruments, 2007) was used to process the data. Data from all three channels (Axes X, Y and Z) was summed and full-wave rectified. Onset of movement was defined as the time at which acceleration broke a threshold of 2 standard deviations above the mean of a 100ms baseline taken during rest. The same process was applied to the detection of object contact when acceleration was detected in the cylinder. During each reach, the greatest value from the trunk accelerometer was recorded as the peak trunk acceleration value in g's (acceleration due to gravity). This measure was used as reflection of the occurrence of trunk compensation used to accomplish each task. To determine the effect of task difficulty and arm used (affected versus unaffected arm) on movement time, a two-way mixed ANOVA was performed for each individual patient. Two-way mixed ANOVA was also performed to determine the effect of task difficulty and arm on peak trunk acceleration. Post-hoc Tukey's test was used to further examine any significant effects.

6. Results – Study 1

6.1 Hypothesis 1A: Decreased impairment will result in a higher overall affected arm reach percentage

There was no correlation between impairment, as assessed by the average of CMSA arm and hand scores, and overall reach percentage {$r_s(8)= -0.274$, $p=0.610$} (Figure 3). Examining individual values shows that there were a number of patients with greater impairment who had a higher affected arm reach percentage than those with more mild impairment. There were also four patients, all non-dominant affected, who did not perform any reaches. One of these patients did have a severe impairment, and was only capable of completing tasks 1 and 2. However, the other three patients could complete all tasks and one patient was considered 'normal' according to the CMSA.

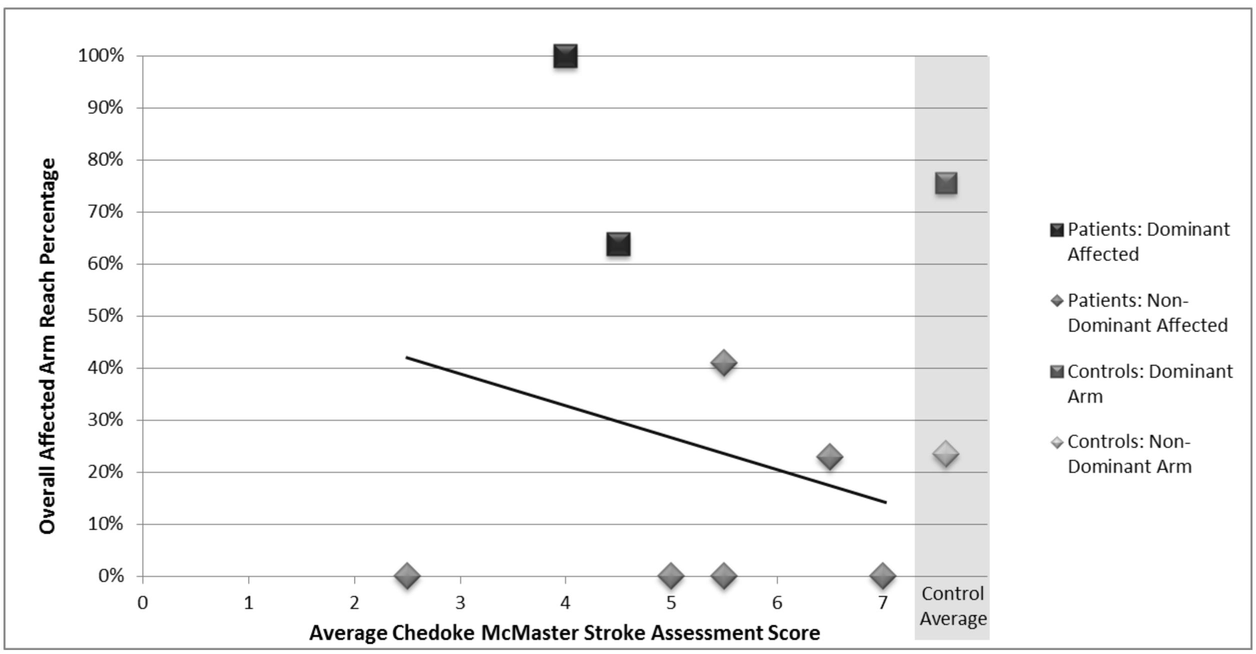


Figure 3: Impairment (average Chedoke McMaster Stroke Assessment score) and overall reach percentage for individual patients with their dominant (black squares) and non-dominant (dark grey diamonds) arm affected. Line of best fit shows correlation for patients ($r = -0.274$, $p = 0.610$). Points in shaded area indicate overall means for controls' dominant and non-dominant arm reach percentage.

6.2 Hypothesis 1B: Patients with their dominant arm affected will have a higher overall reach percentage than those with their non-dominant arm affected

The difference in overall reach percentage between patients with their dominant and non-dominant arm affected was near significance ($p = 0.056$) (Figure 4). This was despite lower CMSA scores for the two patients with their dominant arm affected compared to the patients with their non-dominant arm affected (Arm 5.2 versus 3.5; Hand 5.5 versus 5). Healthy participants had a significantly higher overall reach percentage with their dominant arm compared to their non-dominant arm ($p < 0.001$).

When the non-dominant arm was affected, a floor effect was observed in four of six patients (CMSA Arm 3-7; Hand 2-7), as they performed all reaches, regardless of position or difficulty, with the unaffected, dominant hand. This was despite the ability to carry out some or all of the required tasks, as assessed in the 'forced' condition. The exception to this finding was with 2 patients who reported being fairly 'ambidextrous'; these patients did perform reaches with their affected limb. The first patient (CMSA Arm 7, Hand 6), was born left-hand dominant, but was forced to write with the right hand. Therefore, although handedness questionnaires indicated left-hand dominance, the patient had been writing with the right (affected) hand since age 6. The second patient (CMSA Arm 6, Hand 5), was a dentist prior to the stroke and reported having above average dexterity and strength in both hands due to the high motor skill demands of the profession, as well as a high motivation to regain pre-stroke level of function.

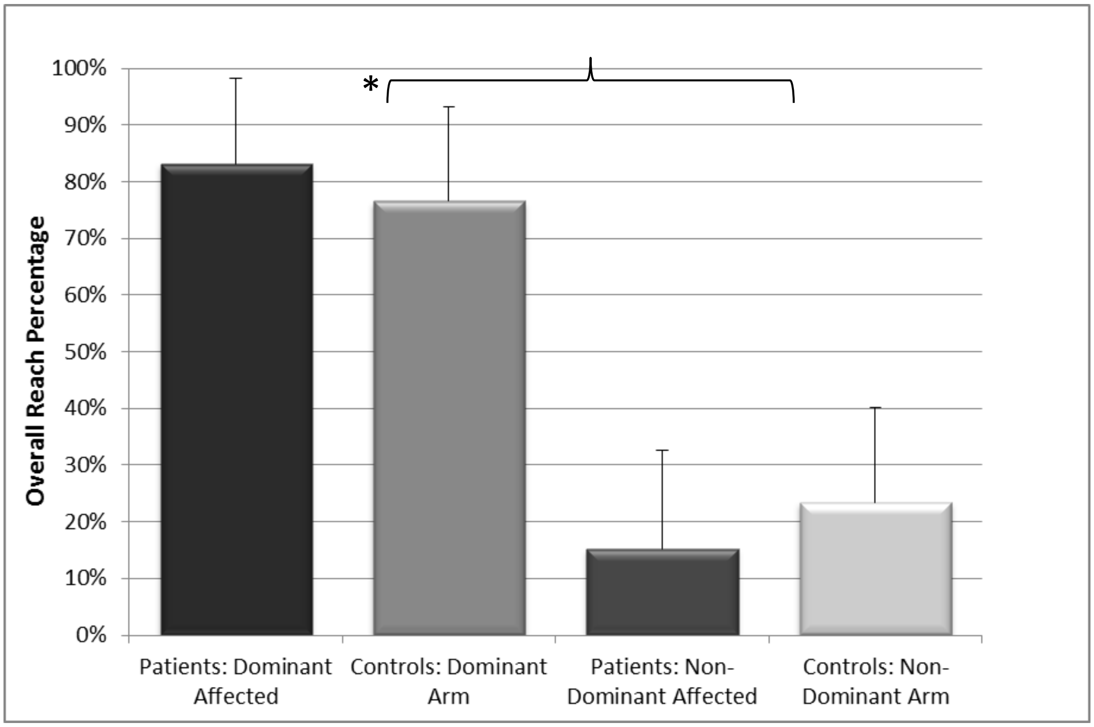


Figure 4: Overall affected arm reach percentage for dominant and non-dominant affected patients compared to the dominant and non-dominant arms in the control group. Controls' dominant arm reach percentage was significantly greater than their non-dominant arm ($p<0.001$). Bars represent means with standard error.

6.3 Hypothesis 2 – Affected arm reach percentage will decrease as task difficulty increases

The DA patients (N=2) performed a maximum of reaches in ipsilateral space, regardless of task difficulty (Figure 5). At midline, affected arm reach percentage was also at a maximum except for a drop at task 4. In contralateral space, affected arm reach percentage decreased from 83% in task 1 to 50%in task 3 where it remained stable. For the 'ambidextrous' patients (N=2), most of the affected arm reaches were in ipsilateral space, but affected arm use decreased as task difficulty increased. Very few affected arm reaches were performed by the 'ambidextrous' patients at midline, even fewer in contralateral space, and these also decreased as task difficulty increased (Figure 5). The remainder of the NDA patients did not perform any reaches, therefore no effect of task could be seen.

Control subjects made a maximum of dominant arm reaches in ipsilateral space (with respect to the dominant arm), and decreased gradually as the tasks were located further into contralateral space to a minimum of approximately 30% dominant arm reaches at the furthest target (Figure 6).   For tasks 1 through 4 there was little difference observed in dominant arm reach percentage, with an average of 85% at midline and 40% in contralateral space for the first four tasks. However, for the final and most difficult task (task 5), participants had a higher reach percentage with their dominant arm in midline (93%) and contralateral space (59%), compared to the first four tasks.

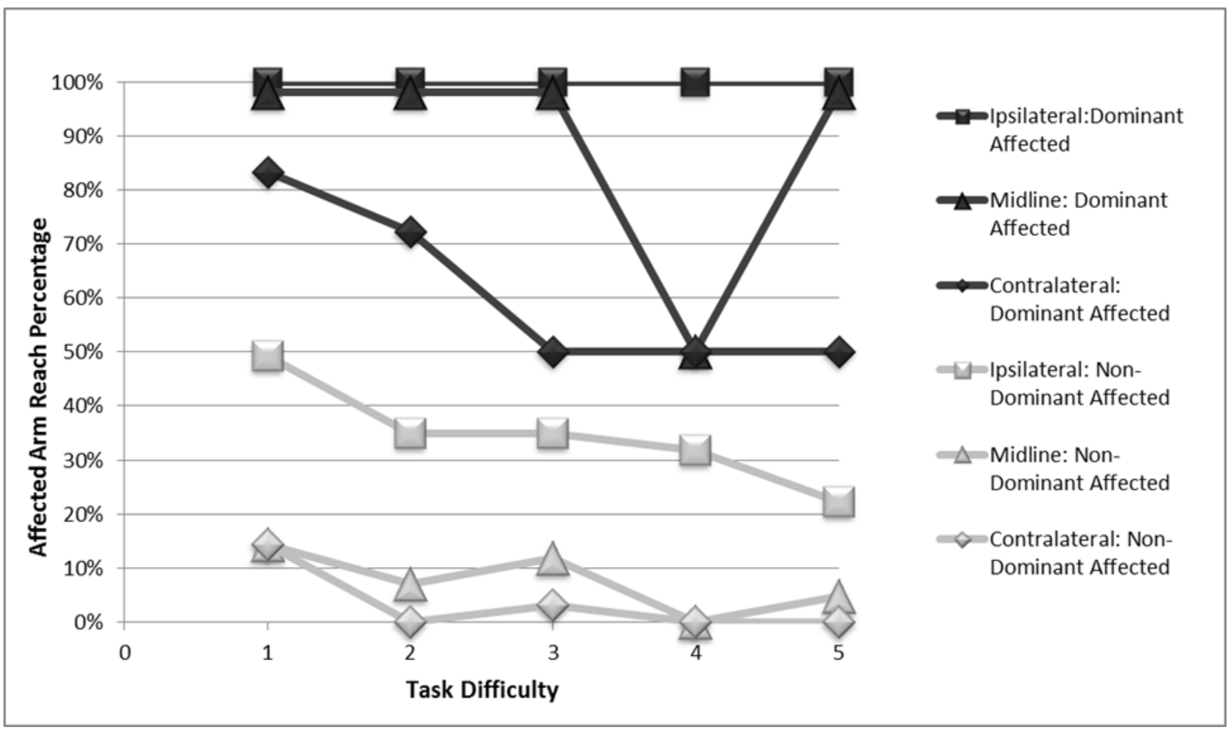


Figure 5: Task difficulty and mean affected arm reach percentage in ipsilateral, midline and contralateral space. Dark grey lines represent affected arm reaches for patients with their dominant arm affected, and light grey patients with their non-dominant arm affected.

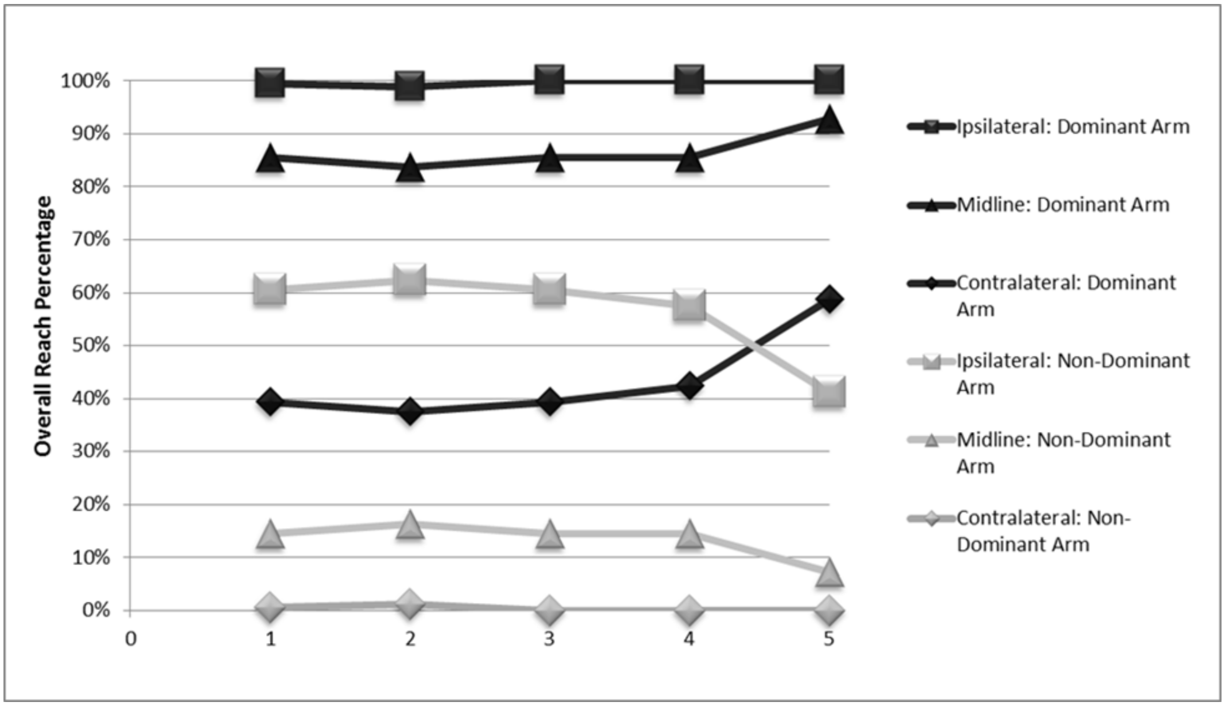


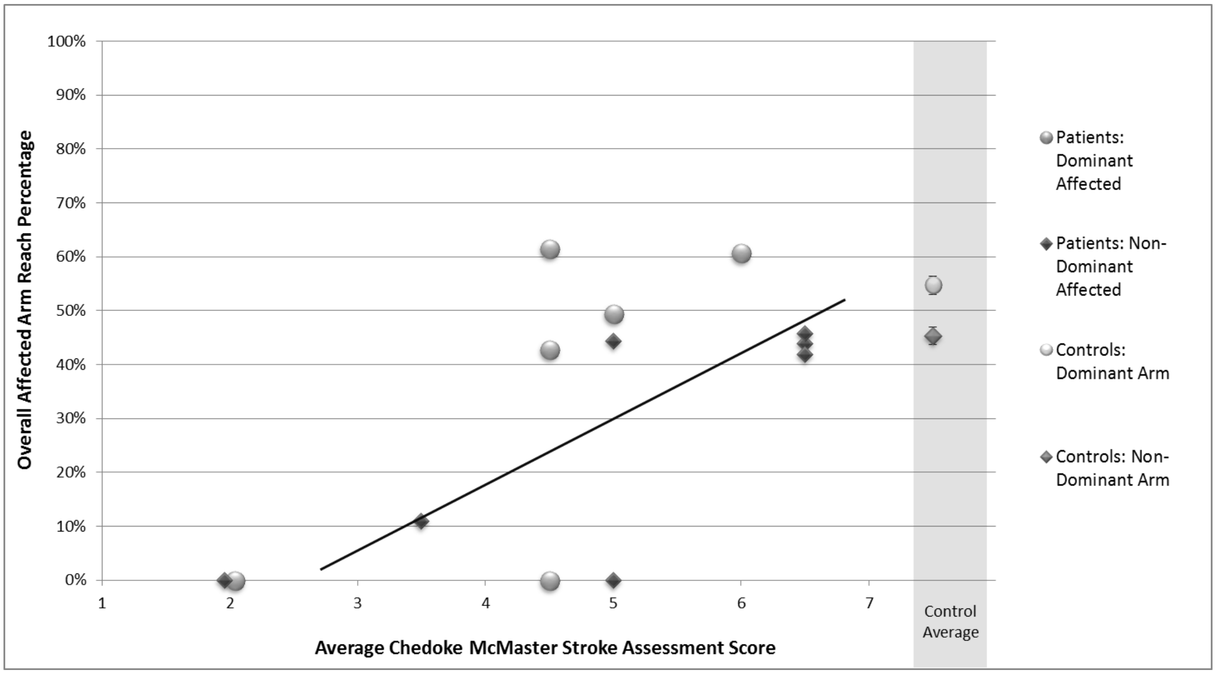
Figure 6: Task difficulty and mean reach percentage for controls in ipsilateral, midline and contralateral space. Dark grey lines represent dominant arm reaches and light grey represents non-dominant reaches.

7. Results – Study 2

The results from study 2 are described in two main sections. The first section describes overall group and subgroup differences as they related to the experimental hypotheses. The second section provides details of individual cases to highlight person specific differences. The latter was considered important given the significant degree of between subject variability measured in the current study.

7.1 Hypothesis 1A: Decreased impairment will result in a higher overall affected arm reach percentage

There was a positive correlation that approached statistical significance comparing between impairment, as assessed by CMSA and overall reach percentage $\{r(13)= 0.458, p=0.068\}$. Figure 7 illustrates this relationship; however, it is apparent that this trend does not apply to all individuals. This is specifically evident for patients 4 and 5 who did not perform any reaches with their affected arm despite their ability to do so when instructed; whereas other patients at the moderate impairment level (CMSA 4,5) had a reach percentage between 40-60%. Qualitatively, as impairment decreased when grouped by impairment level, overall affected arm reach percentage tended to increase (Figure 8). It is interesting to note that there were some important exceptions to this trend. For example, compared to the controls, two dominant affected patients (one with moderate impairment and one with mild impairment), had a higher percentage of affected arm use that would not be predicted based on impairment. The arm use was higher than the controls' dominant average (61 and 62% versus 55%). All three non-dominant affected with mild impairment (range 42-45%) were clustered close to the controls' non-dominant reach average (45%).



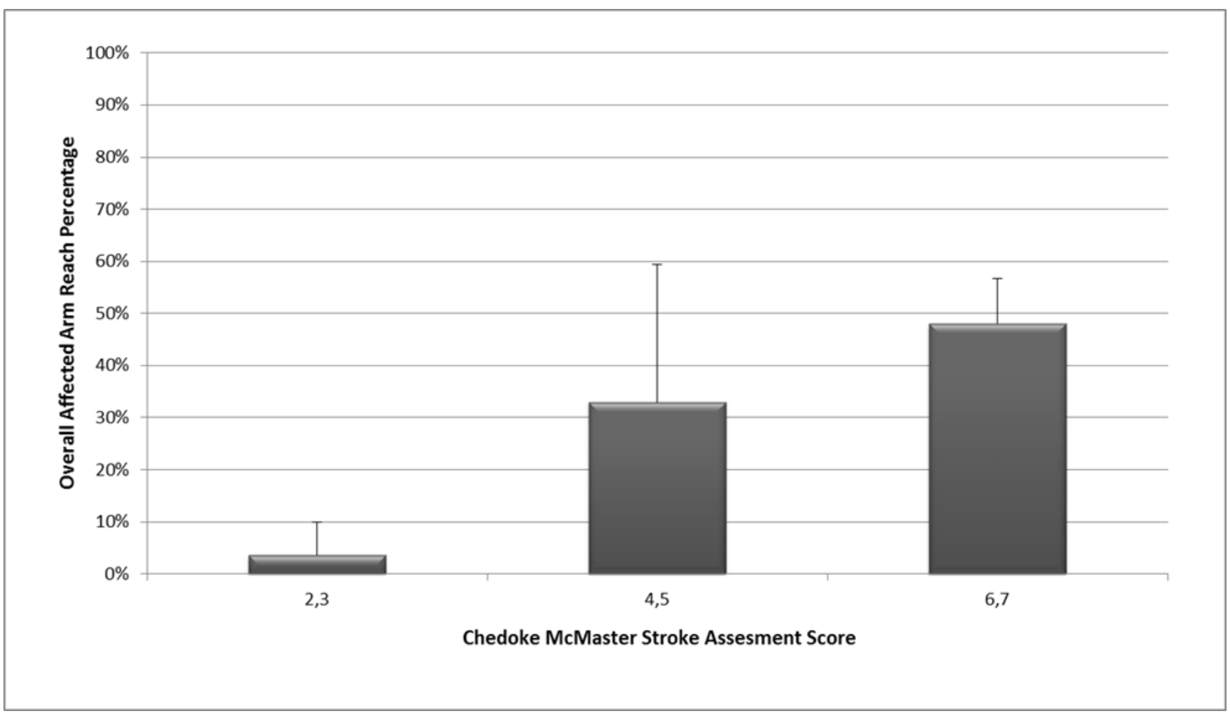


Figure 7: Impairment (average of arm and hand scores on Chedoke McMaster Stroke Assessment) and affected arm reach percentage for patients with their dominant and non-dominant arm affected. Line of best fit shows near significant correlation between impairment and reach percentage ($r=0.458$, $p = 0.068$). Shaded area shows the averages for the controls' overall reach percentage for dominant and non-dominant arms.

Figure 8: Overall affected arm reach percentage for severe, moderate and mild impairment groups. Qualitatively, as impairment becomes less severe, overall affected arm reach percentage increased. Bars represent group means with standard error bars.

7.2 Hypothesis 1B: Patients with their dominant arm affected will have a higher overall reach percentage than those with their non-dominant arm affected

This hypothesis was not supported as there was no statistically significant difference between the NDA and DA group ($Z = 0.857$, $p = 0.196$). Figure 9 shows the overall reach percentage for the controls' dominant and non-dominant arms, compared to the overall affected arm reach percentage of the DA and NDA groups. Despite a comparable difference in overall reach percentage between the dominant and non-dominant arms in the controls and patients, there was only a statistically significant difference measured among the control subjects ($Z = 3.576$, $p<0.001$), due to the high variability amongst patients. The overall reach percentage with the affected arm for the DA group ranged from 0 to 61% across patients, with an average of 35% (+/- 29%), compared to the controls' dominant arm average of 55% (+/-1.7) ranging from 51 to 57%. For the NDA group, use of the affected arm ranged from 0 to 46% across patients, with an average of 26% (+/- 22%), whereas healthy non-dominant arm percentage averaged 45% (+/-1.7) and ranging from 43 to 49%.

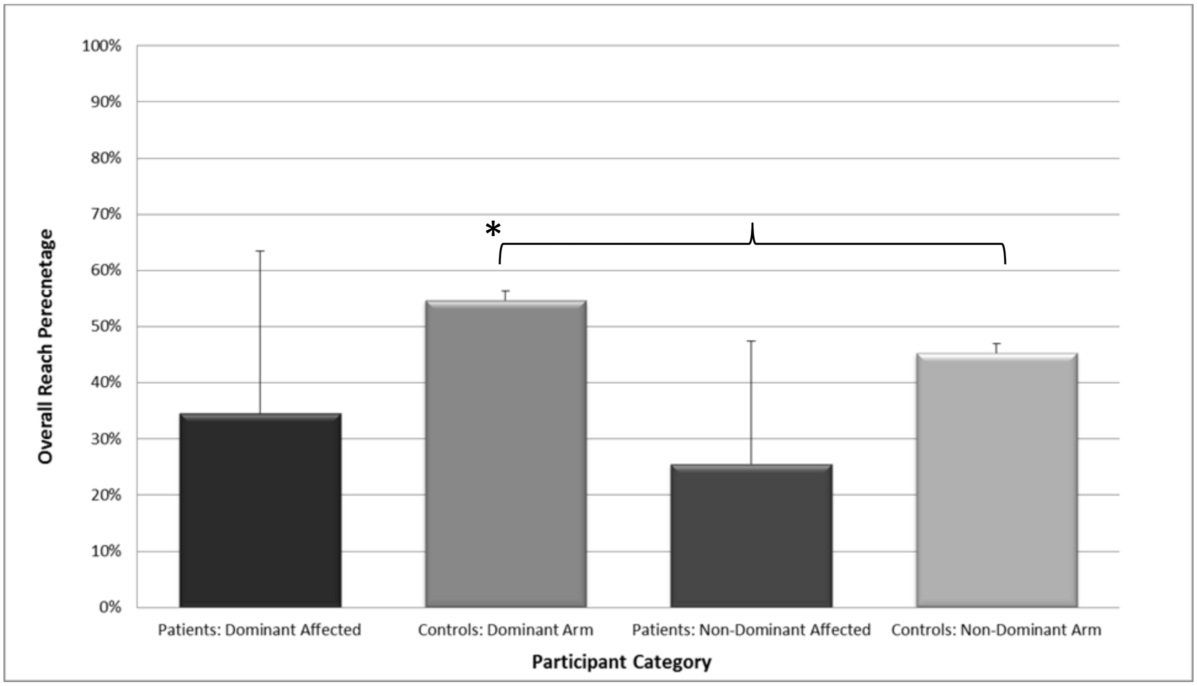


Figure 9: Overall reach percentage across all tasks and positions. Values are for affected arm reaches in patients with either dominant or non-dominant arm affected, and in controls values are for dominant or non-dominant. Reach percentage for the controls' dominant arm was significantly higher than the non-dominant arm. Bars represent means with standard error bars.

7.2.1 Position and Reach Percentage:

The characteristics of the profile of arm use with respect to workspace location were dependent on the subject group (see Figure 10). Overall there was no statistically significant difference between overall reach percentage between the DA and NDA patient groups. However, examining the breakdown of reaches in the three areas of workspace (ipsilateral, midline, contralateral) reveals some differences between groups. The distribution of reaches across these areas in workspace compared to the control subjects is also illustrated in Figure 10. Mean values for the DA and NDA group for ipsilateral reaches were 61.1 and 60.1% respectively, with no statistically significant difference between the two groups ($Z = 0.500$, $p = 0.309$). At midline there was a near significant difference between DA (41.4%) and NDA (9.5%) ($Z = 1.571$, $p =$

0.058). Finally, in contralateral space there was a statistically significant difference between DA (7.6%) and NDA (0%) ($Z = 2.000$, $p = 0.023$).

For the controls, reaches were at a maximum for the dominant arm in all 3 ipsilateral positions, 76% at midline, 6% at the nearest contralateral position and zero for the two furthest contralateral positions (Figure 11). Non-dominant use was also near 100% in ipsilateral space, with a steep drop to 24% at midline and no reaches to any contralateral positions. Although the patient groups had lower reach percentage values when compared to the controls, a similar profile was exhibited when comparing dominant and non-dominant arm use in both patients and controls (Figure 11). Dominant arm use showed a more gradual decline as the target position was located further away from that limb, in contrast, non-dominant arm use dropped sharply at the midline position. In summary, both stroke patients and control subjects were most likely to use the hand closest to the target location, and would, on average, use the dominant arm for the majority of tasks when the target was equidistant.

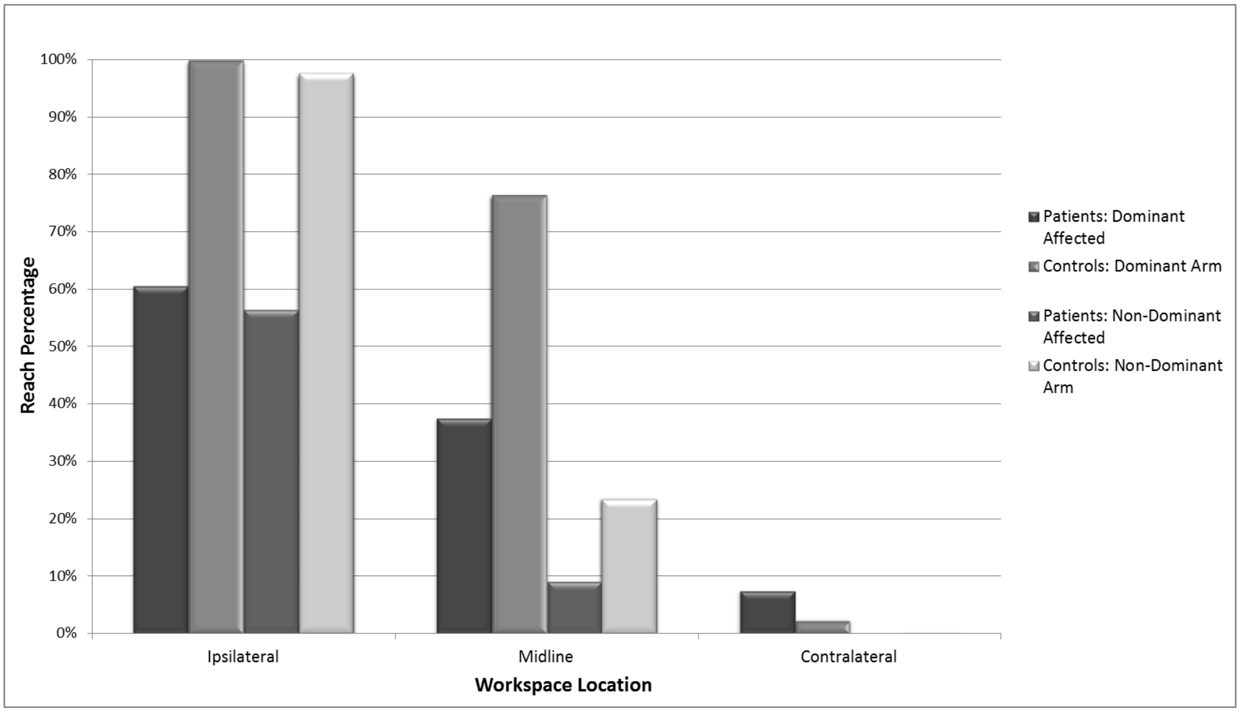


Figure 10: Workspace location and group average reach percentage for patients' affected arm and controls' dominant or non-dominant arm. The dominant affected average was significantly greater than the non-dominant affected average in contralateral space, and was almost significantly greater at midline.

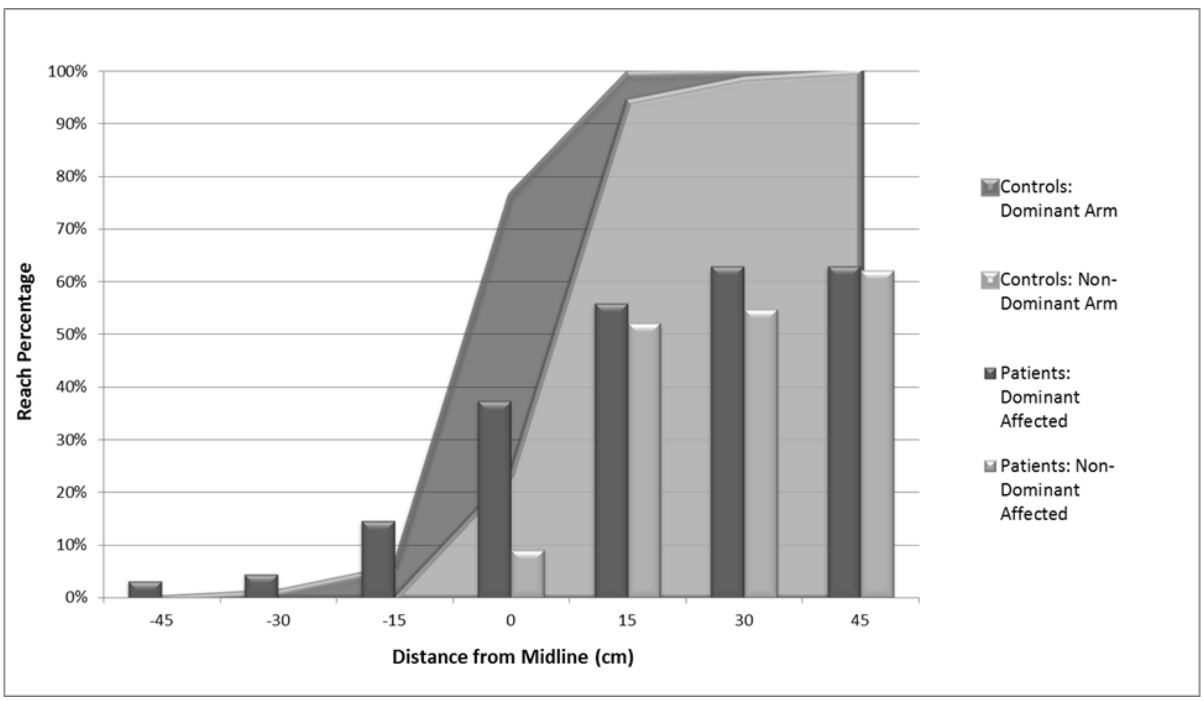


Figure 11: Reach percentage and task position for patients' affected arm and controls' dominant or non-dominant arm. Line area shows group average of reach percentage for controls' dominant and non-dominant arms, bars show affected arm reach percentage for patients with dominant or non-dominant arm affected.

7.3 Hypothesis 2: As task difficulty increases, affected arm reach percentage will decrease

Tasks in increasing order of difficulty (from 1 to 5) consisted of: reach to a fixed cylinder, reach to a free standing cylinder, reach and grasp the fixed cylinder, reach and grasp the free cylinder and pick up and place a dime. Overall, there was no statistically significant difference in total affected arm reach percentage across task difficulty {$F(4,11 = 0.141$, $p = 0.966$ }, pre-stroke dominance {$F(1,11) = 0.362$, $p = 0.560$} or an interaction between task and pre-stroke dominance {$F(4,11) = 1.431$, $p = 0.240$}.

Although there was no statistical effect of task difficulty, pre-stroke dominance or an interaction, the relationship between these factors is shown in Figure 12. Qualitatively, as task difficulty increased, the DA group showed a weak positive relationship between task difficulty and percentage of affected arm use, whereas the NDA showed a weak negative relationship (Figure 12). In other words, when the non-dominant arm was affected by the stroke there was a tendency to rely on the unaffected limb as tasks became more challenging. This resulted in a steady increase in the discrepancy between amount of affected arm use between the DA and NDA groups, with the smallest difference for task 1 (3%), increasing slightly for the next 3 more difficult tasks and reaching a maximum difference in task 5 (19%). Qualitatively, in the controls (Figure 12), there was a similar weak positive trend for dominant arm use and a weak negative trend for non-dominant use. There was also an increase in the discrepancy between the dominant and non-dominant reach percentage as task difficulty increased (smallest at task 1: 3.5% and largest at task 5: 16%). In summary, both patients and controls were more likely to use their dominant arm as task challenge increased, resulting in increased use of the affected arm in DA patients and a decreased use of the affected arm in NDA patients.

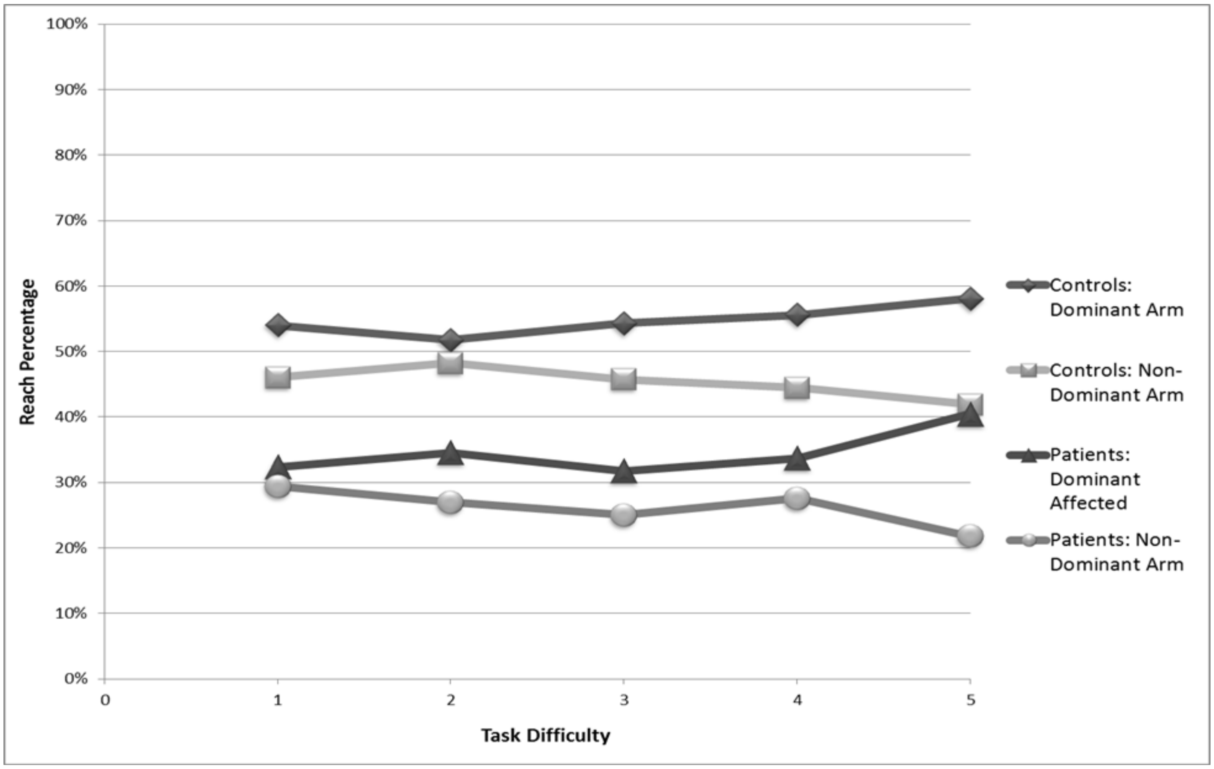


Figure 12: Increasing task difficulty and reach percentage across positions for patients' affected arm and controls dominant or non-dominant arm. Qualitatively, there was a weak negative relationship between increasing task difficulty and non-dominant arm use (patients and controls), and a weak positive relationship between task difficulty and dominant arm use (patients and controls).

7.3.1 Task Difficulty, workspace location and pre-stroke dominance:

The discrepancies in amount of affected arm use between the DA and NDA patients are greater in midline and contralateral space, but are relatively modest in ipsilateral space (Figure 13). Qualitatively, for the DA group, affected arm reach percentages decreased in midline and contralateral space from task 1 to task 4, but then reached a maximum for the most difficult task 5. In contrast, as task difficulty increased for the NDA group, their reach percentage showed an apparent trend of constant decline at midline space, from 13% in task 1 to zero in task 5 (no contralateral reaches for any task). This created a discrepancy of 25% between affected arm reaches at midline for task 1, up to 50% in task 5. In contralateral space, affected arm reach percentage was 11% higher in the DA group for task 1 and 20% higher in task 5.

Figure 14 displays data from controls separately by dominant and non-dominant arm use to illustrate the effect of increasing task difficulty and workspace location on reach percentage. Given that reach percentage was already at 100% in ipsilateral space, there was no change in dominant arm use as task difficulty increased. However, at midline dominant arm use did increase from task 1 to 5, except for a drop at task 2. Similar to the patients, this resulted in a greater discrepancy at midline between dominant and non-dominant arm use as task challenge increased, from 40% in task 1 to a maximum of 74% in task 5. In general, patients decreased affected arm use as tasks required greater distal control, regardless of pre-stroke dominance. However, when the task required fine control to manipulate an object, DA patients reached further with their affected arm, whereas NDA patients did not reach any further than target locations in ipsilateral space.

In contrast to the patient group, the controls had very few contralateral reaches with the dominant arm; therefore, increasing task difficulty had no influence on contralateral reach percentage. The exception to this was an increase in dominant arm use to 16% at the nearest contralateral position for the most difficult task 5 (compared to 0-6% for all other tasks). In summary, the effect of task difficulty was only evident in controls when comparing hand preference in task 5. For all other tasks the arm used was the one closest to the target location, with the dominant arm performing the majority of tasks when the target was equidistant.

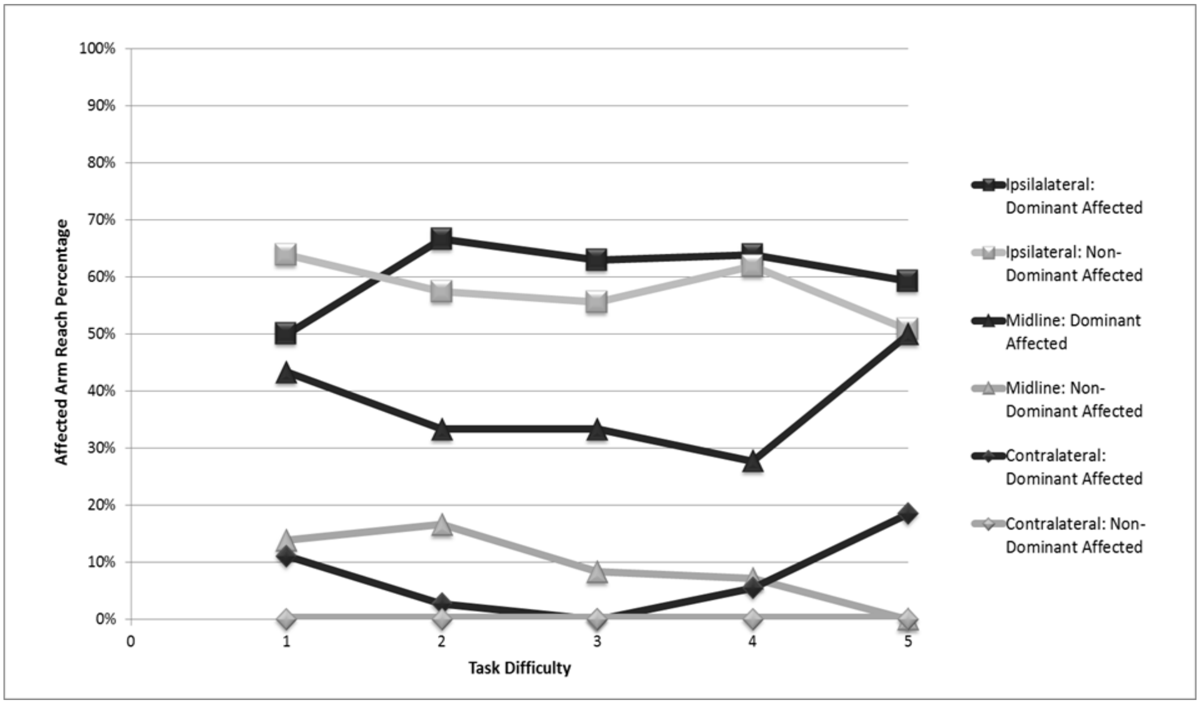


Figure 13: Task difficulty and mean affected arm reach percentage in ipsilateral, midline and contralateral space. Dark grey lines denote affected arm reaches for patients with their dominant arm affected, and light grey denotes patients with their non-dominant arm affected. Note the large discrepancy in affected arm use between patient groups for task 5 in midline and contralateral space.

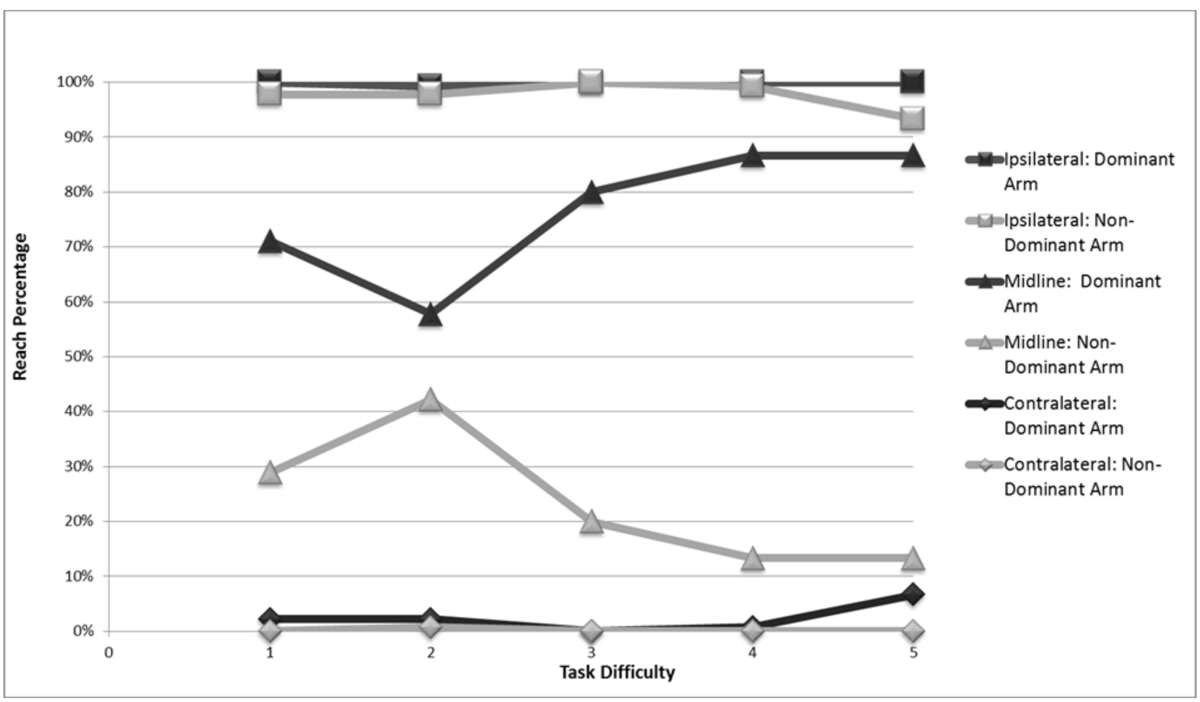


Figure 14: Task difficulty and mean reach percentage for controls in ipsilateral, midline and contralateral space. Dark grey lines represent dominant arm reaches and light grey represents non-dominant reaches. Note the large discrepancy between dominant and non-dominant reach percentage at midline for task 5.

7.4 Kinematic Data

7.4.1 Movement Time

All movement times and peak trunk acceleration values will only be reported for reaches made into ipsilateral space, as the midline and contralateral reaches were a longer distance and would have been characterized by longer movement time and different peak trunk acceleration. This would not have affected participants equally as most patients and controls performed more reaches to midline and contralateral space with their dominant arm.

Due to the heterogeneity, the effect of task difficulty and pre-stroke hand dominance on movement time was analyzed using two-way mixed ANOVA for each individual patient; these results are summarized in Table 3. Note that the individual case details are provided in the following section. Four patients were not included in the analysis; patients 1 and 2 could not complete any tasks with the affected arm, and patients 5 and 6 did not perform enough affected arm reaches to allow analysis. There was an effect of task on movement time in eight of nine patients analyzed; however, for most patients the effect was largely due to time required to complete the most difficult task 5. All patients with an average CMSA score of 5 (n=5) or lower performed significantly slower with their affected arm; whereas this was true for only one of four patients with a score above 6. An interaction between pre-stroke hand dominance and task difficulty was observed in 4 patients, with impairment scores ranging from 3.5 to 6.5. For the most severe patient, the interaction was due to an increase in movement time matched to the increase in task challenge, whereas the increasing task difficulty had little effect on the unaffected arm. The remaining three patients also had a significant effect of hand but the interaction effect revealed that the hand effect was due to a large discrepancy between the affected and unaffected movement time values in task 5, and not in any other tasks. Therefore, of all the patients with an effect of hand, there were only 3 patients (all below CMSA 5) who were significantly slower with their affected arm across all tasks.

Table 3: Significant main effects of task, hand and the interaction of task and hand on movement time and peak trunk acceleration for individual patients. Shaded boxes indicate significance ($p<0.05$), determined using two-way mixed ANOVA on patients who completed tasks voluntarily with the affected arm.

Patient Number	**CMSA Score**	**Movement Time**			**Peak Trunk Acceleration**		
		Task	Hand	Task*Hand	Task	Hand	Task*Hand
3	3.5	■	■	■	■		■
6	5		■		■		
7	4.5	■	■		■	■	
8	4.5	■	■	■			
9	5	■	■	■	■	■	■
10	6.5	■	■	■		■	
11	6.5	■			■	■	
12	6.5	■			■	■	
13	6	■			■		

Figure 15 illustrates the average movement time values for each impairment group as task difficulty increased. There was only one patient with severe impairment (patient 3), capable of completing tasks voluntarily, and this patient was only able to complete tasks 1 through 4. Overall, the mild impairment group had the fastest movement times across all tasks, except in task 5 where both the mild and moderate impairment groups had very similar values (patient 3 could not complete task 5). For tasks 1 and 2 the moderate impairment group was actually slower than patient 3 (severe impairment). However, as the task difficulty continued to increase, the movement time of patient 3 also increased, whereas the increasing task difficulty had a much smaller effect on both the moderate and mild impairment groups. This resulted in the patient with severe impairment having the slowest movement times for tasks 3 and 4.

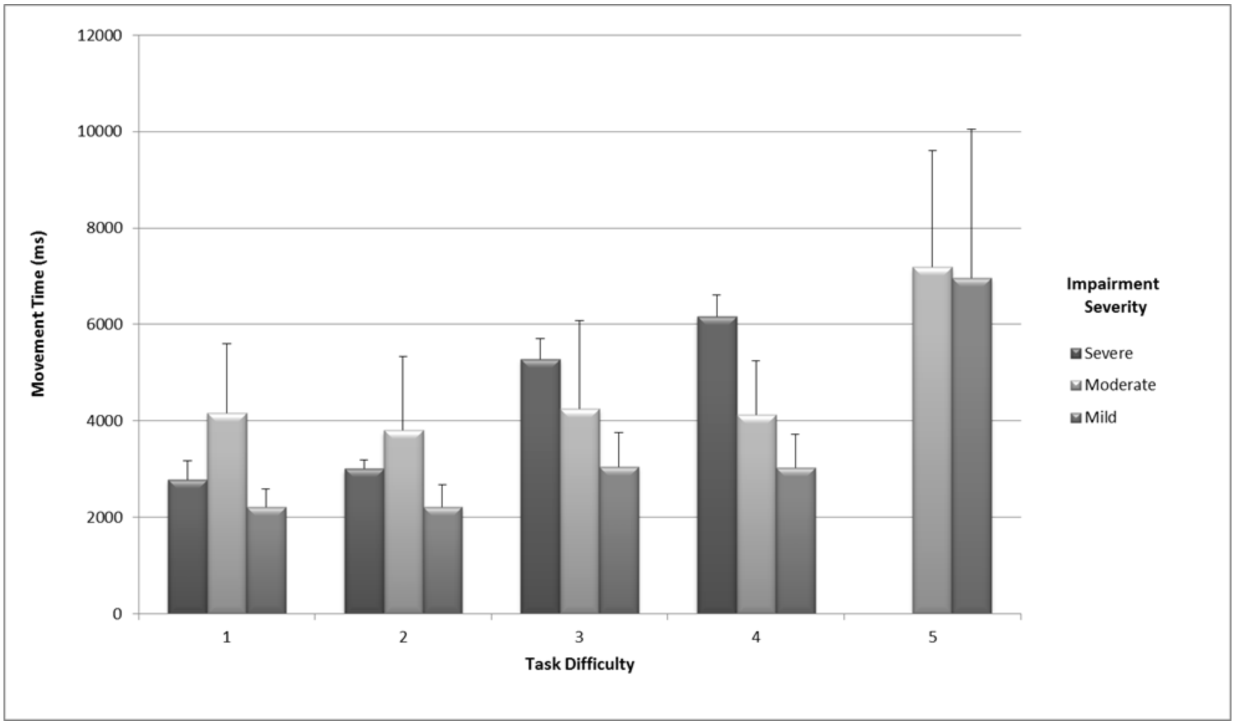


Figure 15: Affected arm movement time for severe, moderate and mild impairment groups for tasks 1 to 5. Qualitatively, the patient with severe impairment shows a steady increase in movement time as task difficulty increases, whereas mild and moderate groups only increase for task 5. Bars indicate means with standard error bars.

7.4.2 Peak Trunk Acceleration

Overall, for peak trunk acceleration, there was an effect of task measured in 7 of 9 patients, an effect of pre-stroke hand dominance in 5 of 9 patients (2 with moderate impairment, and 3 with mild impairment), and an interaction between task and hand in one patient (moderate impairment). Individual test statistics and significance will be presented in each case study description. Figure 16 illustrates the effect of impairment and task difficulty on peak trunk acceleration. Overall, there appears to be little effect of task or impairment on peak trunk acceleration, with the exception of a very large increase for the patient with severe impairment in task 4. Specifically, differences were small between impairment groups, with overall average values of 0.319g +/- 0.109 for severe impairment, 0.297g +/- 0.160 for moderate and 0.286g +/- 0.054 for mild.

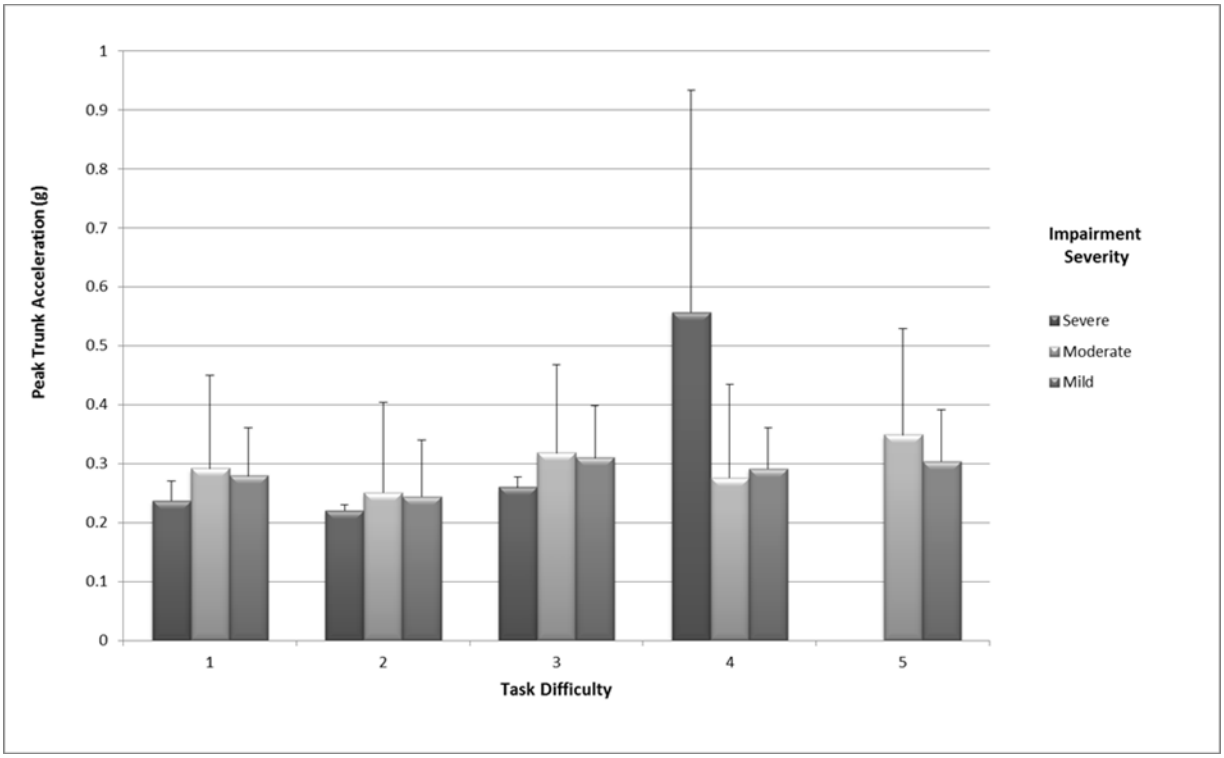


Figure 16: Peak trunk acceleration during affected arm reaches for severe, moderate and mild impairment groups for tasks 1 to 5. Bars indicate group means with standard error bars.

7.5 Case Descriptions: Severe impairment group

7.5.1 Patient 1:

This patient's dominant side was affected, with a CMSA score of 2 for both arm and hand, and they met one level 3 criterion (shoulder shrugging). Shoulder pain was absent but at least one prognostic indicator was present. The level of impairment prohibited any voluntary reaching with the affected limb, thus all tasks were completed with the unaffected, non-dominant arm.

7.5.2 Patient 2:

This patient's non-dominant side was affected and had a CMSA score of 3 for arm, which indicates that the patient is capable of enough arm movement to touch their chin, opposite knee as well as shrug their shoulders. A score of 2 for hand was observed, which indicates only facilitated movements possible and little to no voluntary control. Shoulder pain was intermittent with pain in just the shoulder. The patient did attempt the first task in ipsilateral space with the affected arm; however, finding this extremely difficult, they switched to the dominant, unaffected arm and did not attempt any more reaches with the affected arm for the remainder of the test. Following completion of the test, the patient was asked to attempt the fixed reach again. To initiate movement, the patient used the healthy arm to orient the hand in the correct position and slid the affected arm to the cylinder; however, he was not capable of reaching the full distance and we moved it closer allowing him to make contact. Qualitatively, the reach relied heavily on trunk and shoulder flexion.

7.5.3 Patient 3:

This patient's non-dominant side was affected, with CMSA scores of 4 for arm and 2 for hand. Mild sensory loss was noted, and shoulder pain was absent, but at least one prognostic indicator was present. In spite of the severe degree of impairment, patient 3 was capable of completing all tasks except for task 5, with an overall affected arm reach percentage of 14%. This patient performed a maximum of affected arm reaches for tasks 1 through 4 at the -45cm position (most ipsilateral). The influence of task difficulty was observed at -30cm, as the patient performed 2/3 possible fixed reaches, 1/3 free reaches and 0/3 for each of the grasping tasks. For all other positions the unaffected arm was used to complete all tasks.

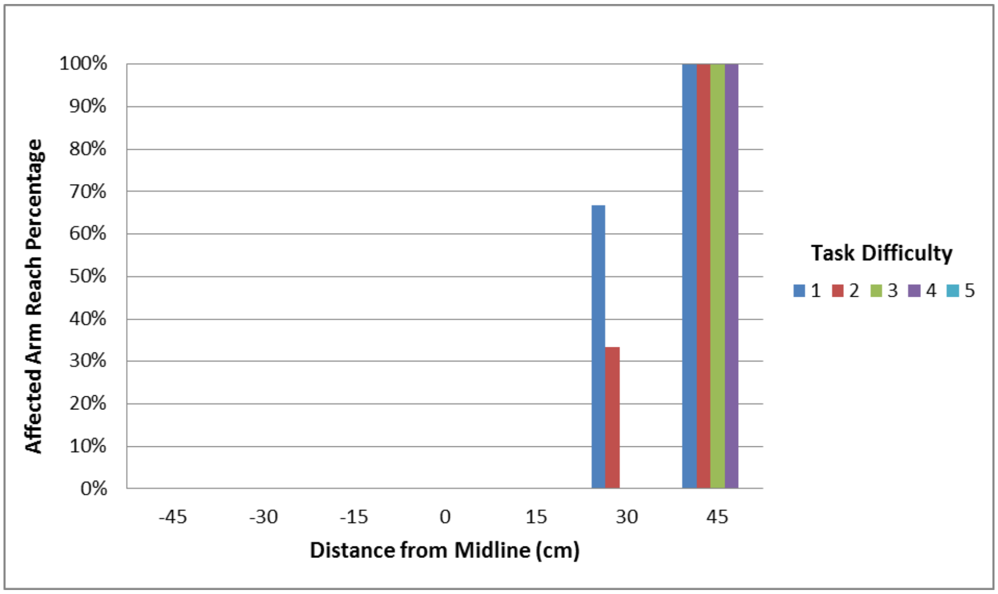


Figure 17: Affected arm reach percentage at each location and for each task difficulty. Patient 3 was only capable of completing tasks 1 to 4 with the affected arm, and performed a maximum of those tasks at the position closest to the affected arm.

Movement Time

Two-way ANOVA revealed a significant main effect of task {$F(3,37) = 102.48$, $p<.0001$}, hand {$F(1,37) = 467.86$, $p<.0001$} and an interaction between task and hand {$F(3,37) = 75.83$, $p<.0001$} on movement time. A post-hoc Tukey's test indicated that movement times were significantly slower for the affected compared to the unaffected arm for each task ($p<0.0001$). The duration of movement was related to the anticipated differences in task difficulty. For the affected arm movement time, tasks 1 and 2 were significantly faster than both tasks 3 and 4 ($p<0.001$). Task 3 was also significantly faster than task 4 ($p< 0.05$). There were no significant differences between movement time values across tasks for the unaffected arm ($p>0.05$).

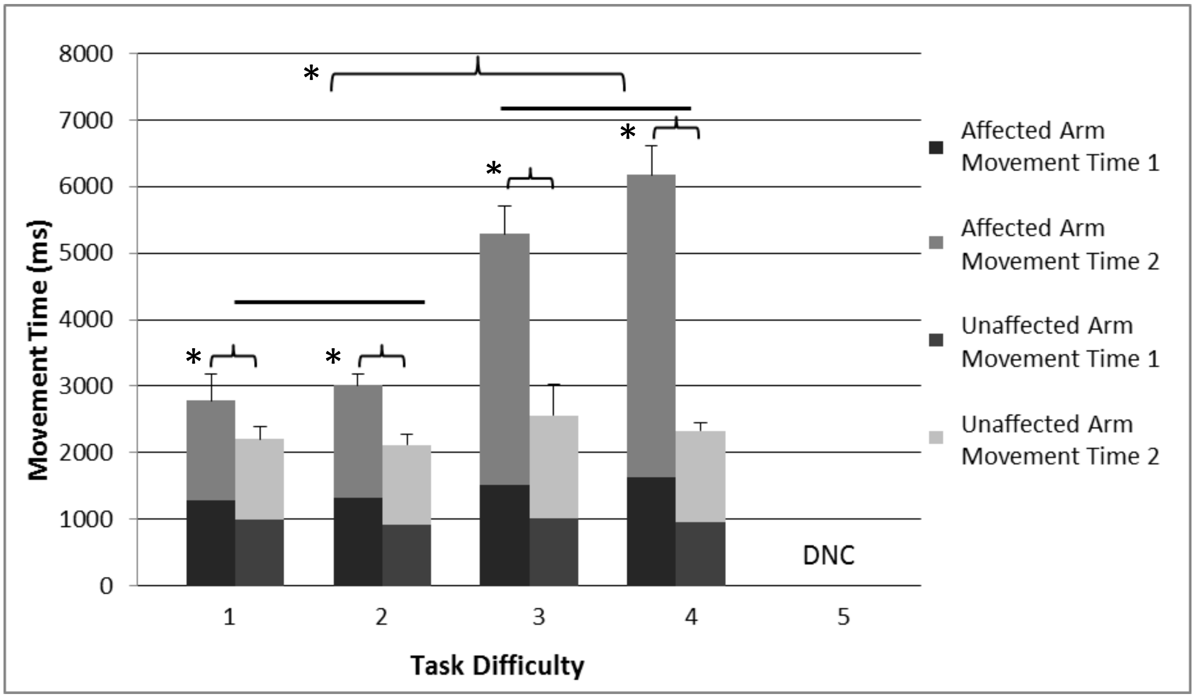


Figure 18: Task difficulty and movement time for the affected and unaffected arm for patient 3. The darker area of the bars represents movement time one, and lighter areas movement time two, with standard error bars on total movement time. Total movement time was significantly slower for the affected arm for all tasks ($p<0.001$). Affected arm was significantly slower for tasks 4 and 3 compared to 1 and 2 ($p<0.05$) and slower for task 4 compared to task 3 ($p<0.05$). Patient 3 could not complete task 5. No significant differences were observed between tasks for the unaffected arm.

Peak Trunk Acceleration

Two-way ANOVA revealed a significant main effect of task {$F(3,37) = 9.84$, $p<0.001$} but not hand {$F(1,37) = 2.0$, $p=.32$} or an interaction between task and hand {$F(3,37) = 0.18$, $p=0.91$}. A post-hoc Tukey's test indicated that peak trunk acceleration was significantly greater for task 4 than each of the first three tasks ($p<0.05$). Qualitatively, peak trunk acceleration was always greater when the affected arm was reaching, with the greatest discrepancy between affected and unaffected arm reaches occurring during task 4 (the most difficult task performed).

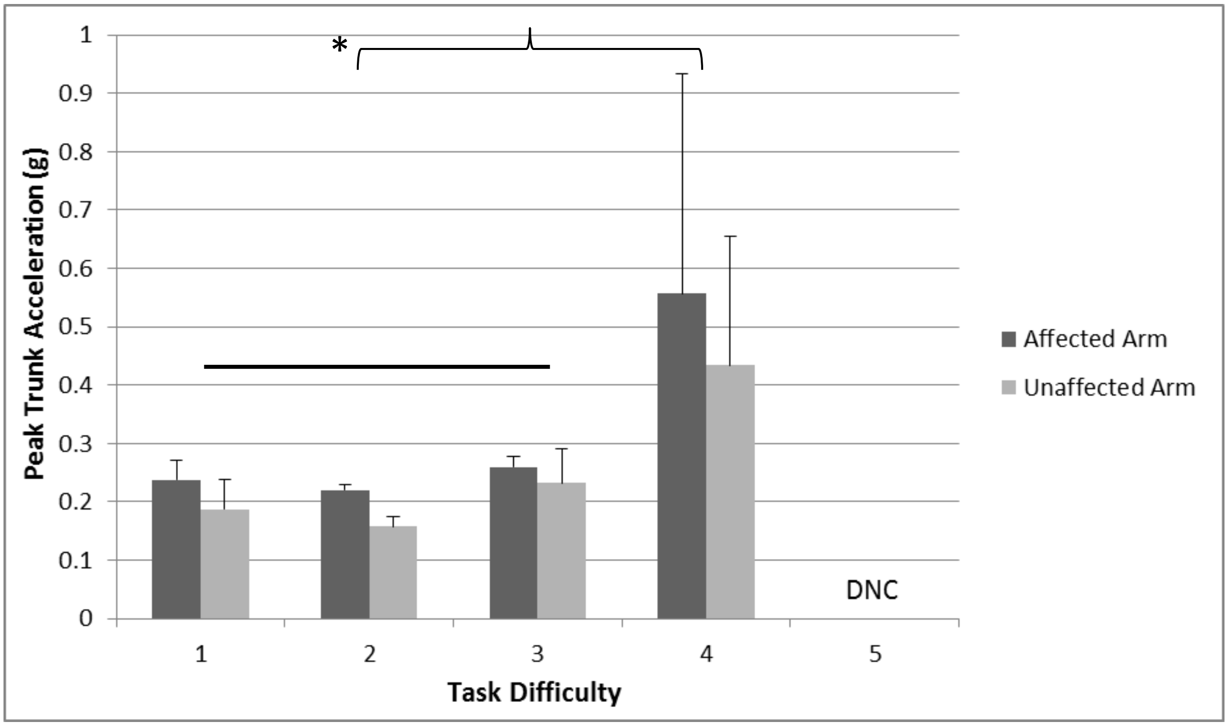


Figure 19: Task difficulty and peak trunk acceleration during affected and unaffected arm reaches for patient 3. Peak trunk acceleration was significantly higher in task 4 compared to all other tasks ($p<0.05$), and there was no effect of hand. Bars represent mean values with standard error bars.

7.6 Case Descriptions: Moderate Impairment Group

7.6.1 Patient 4:

This patient's dominant side was affected, with CMSA scores of 4 for arm and 5 for hand. Motor ataxia, a slight increase in muscle tone at the wrist, and shoulder pain were all present. Shoulder pain was intermittent but was the highest level of pain in this moderate impairment group and this pain interfered with functional activities. In spite of being able to complete all tasks with the affected arm, patient 4 performed all voluntary reaches with the unaffected, non-dominant arm. Therefore, following the voluntary reaches the patient was asked to perform each task with the affected arm.

Movement Time

Compared to the patient's unaffected arm, all tasks with the affected arm were slower, with the largest discrepancies for task 3 (4162 versus 2218ms) and task 4 (5252 versus 2244ms). An increase in the time to make contact with the object contributed to the longer movement times in the grasp tasks (tasks 3 and 4), which was not seen in the majority of patients. Overall average movement time for the affected arm was 4004ms compared to 2257ms for the unaffected arm. However, this patient completed tasks with the affected arm more quickly than others in the moderate impairment group who performed reaches voluntarily with the affected arm, with the exception of task 4.

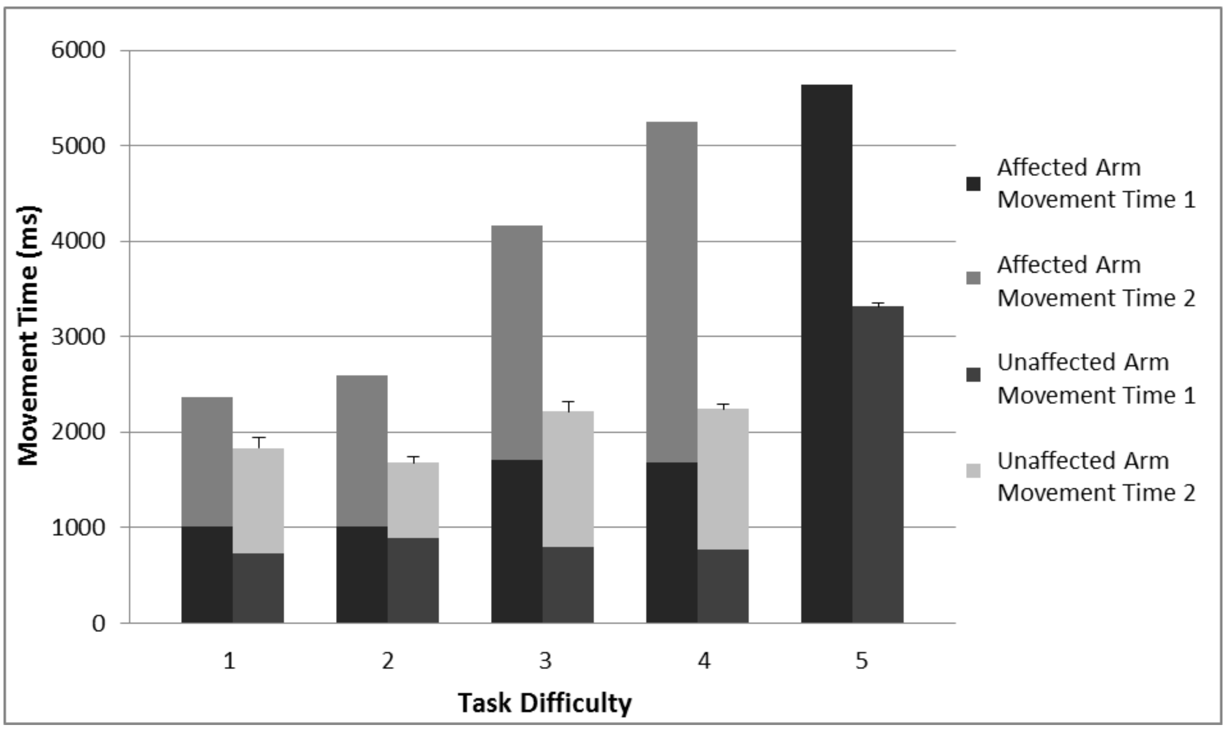


Figure 20: Task difficulty and movement time for the affected and unaffected arm for patient 4. The darker area of the bars represents movement time one, and lighter areas movement time two. Standard error bars are on total movement time, and only for unaffected reaches as there were insufficient trials with the affected arm.

Peak Trunk Acceleration:

Peak trunk acceleration during affected arm reaches was higher than during unaffected reaches for every task, with an overall average of 0.283g affected compared to 0.173g unaffected. In task 1, peak trunk acceleration was 0.162g affected and 0.105g unaffected, which steadily increased as task challenge increased to a maximum of 0.379g affected and 0.304 unaffected.

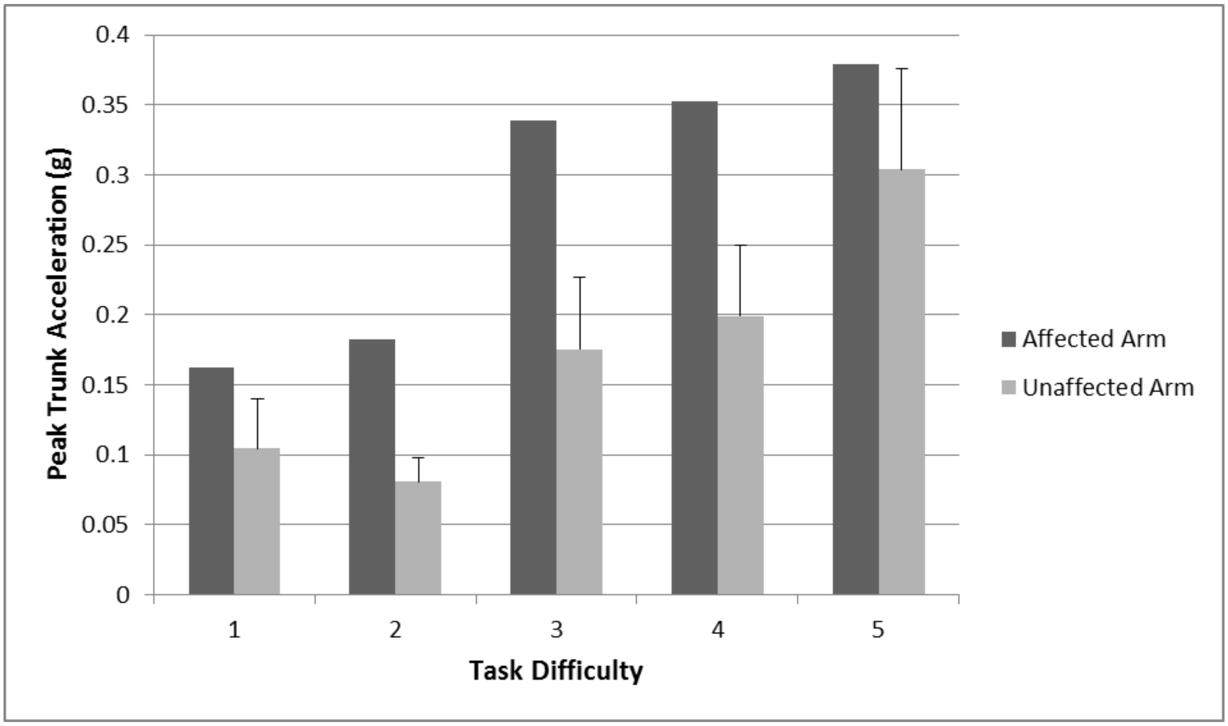


Figure 21: Task difficulty and peak trunk acceleration during affected and unaffected arm reaches for patient 4. Error bars are for unaffected reaches only, as there were insufficient trials with affected arm reaches.

7.6.2 Patient 5:

This patient's non-dominant side was affected, with CMSA scores of 5 for both arm and hand. Slight increases in muscle tone at the elbow and wrist were present as well as motor ataxia; shoulder pain and all prognostic indicators were absent. Despite the capability to complete all five tasks, patient 5 performed all tasks in the voluntary condition with the unaffected (dominant) arm. Similar to patient 4, who also completed all voluntary reaches with the unaffected arm despite possessing the ability with the affected arm, patient 5 also had a score of 2 for motor ataxia. This patient was the only patient in the study to have a reduction in CMSA score of 2 points from the previous visit. At three months after stroke the patient had CMSA scores of 5 and 6 for arm and hand, which improved to 7 and 6 six months post-stroke. At the time of this study, 12 months after stroke, the patient's impairment declined to a CMSA score of 5 for both the arm and hand. On the SIS, Patient 5 also reported a significant drop ($p<0.01$) in his self-rated ability to perform functional tasks, as well as self-rated arm and grip strength, with a decline from 4.25 (range 3-5) to 2.86 (range 2-3), where a score of 5 indicates no difficulty and 0 indicates inability to complete task.

Movement Time

In the required reaches, affected arm movement times rose slightly from task 1 to task 2 and remained steady until task 5, where movement times more than doubled. Movement times were consistently faster with the unaffected arm across all tasks, with an overall average movement time of 5889ms for the affected arm compared to 2811ms for the unaffected arm. In contrast to patient 4, patient 5 took longer to complete all tasks (average of 5889ms) with the affected arm than the other patients in the moderate impairment group (average of 4710).

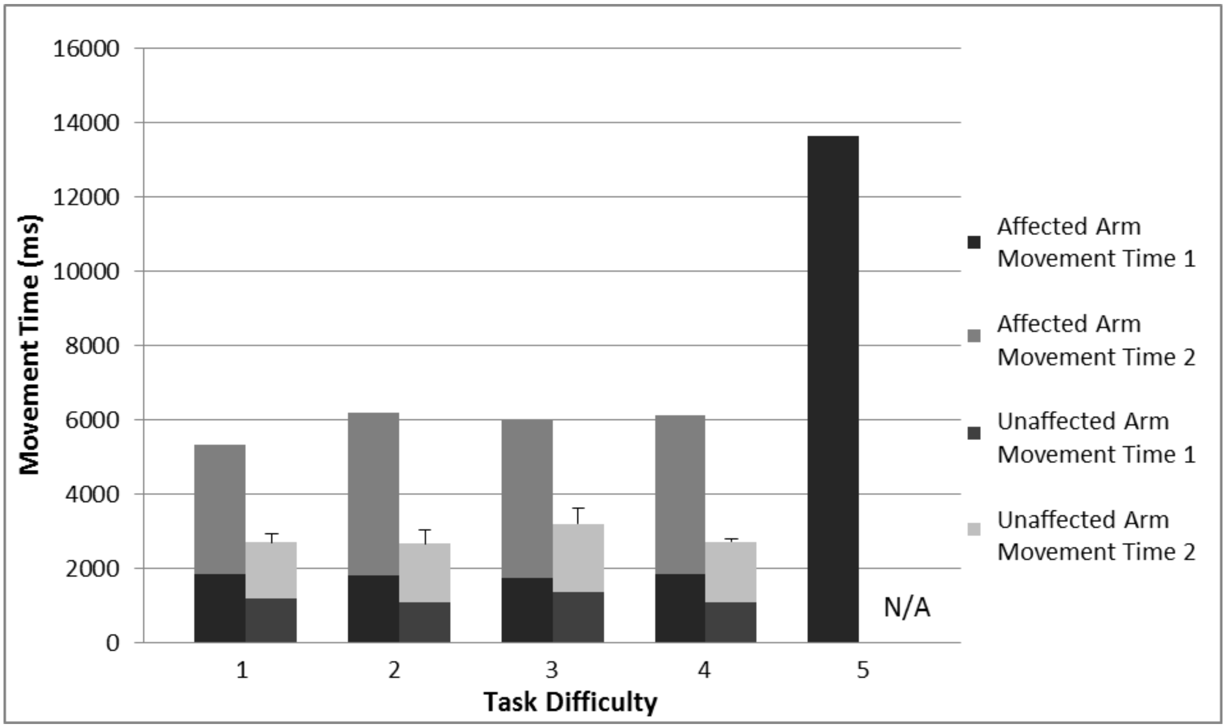


Figure 22: Task difficulty and movement time for the affected and unaffected arm for patient 5. The darker area of the bars represents movement time one, and lighter areas movement time two. Standard error bars are on total movement time, and only for unaffected reaches as there were insufficient trials with the affected arm.

Peak Trunk Acceleration

There was no overall trend for peak trunk acceleration with regard to the increase in task challenge, although peak acceleration was always greater during the affected arm reaches. Overall, average peak trunk acceleration for affected arm reaches was 0.439g compared to 0.217g for unaffected reaches.

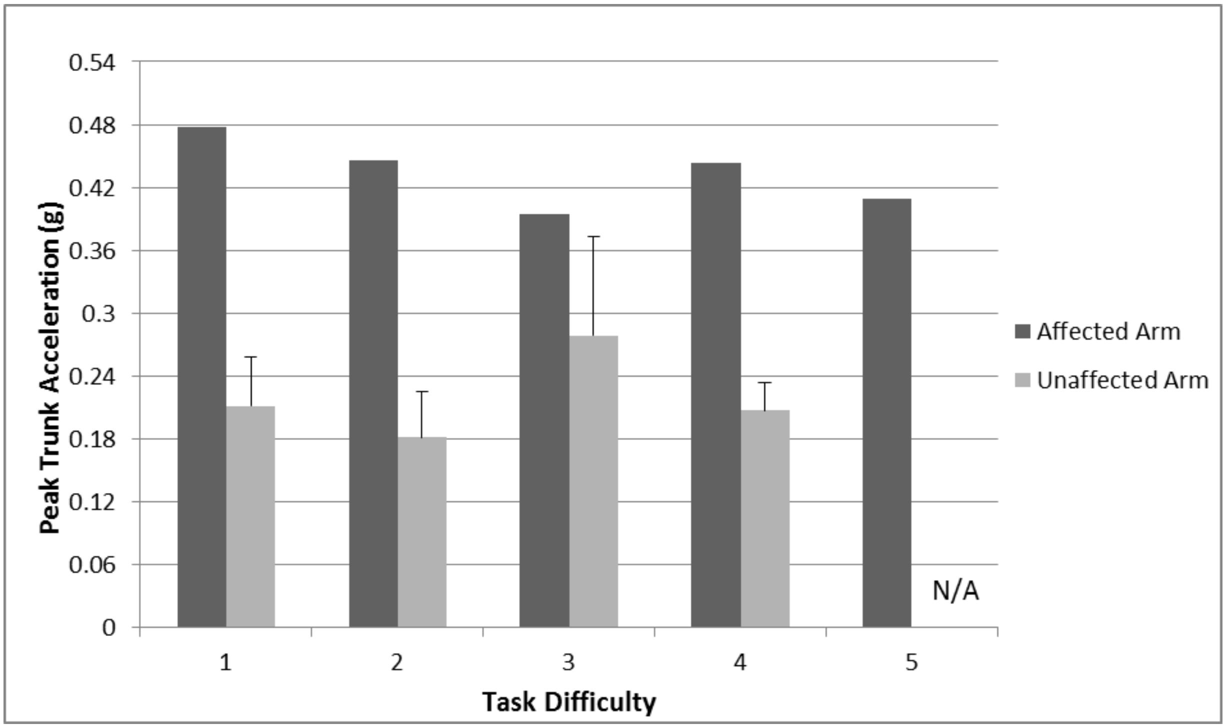


Figure 23: Task difficulty and peak trunk acceleration during affected and unaffected arm reaches for patient 5. Error bars are for unaffected reaches only, as there were insufficient trials with affected arm reaches.

<u>7.6.3 Patient 6:</u>

This patient's non-dominant side was affected, with CMSA scores of 5 for both arm and hand. Shoulder pain was noted but not to a degree that interferes with function. Of note was the patient's slow task completion bilaterally; compared to other patients in the moderate impairment group, average affected arm movement time was 6320ms compared to 4089ms, and 4946ms compared to 3084 ms for unaffected reaches. It was noted by the physiotherapist that the slowness may be attributed to motor planning deficits; however, this was not proven.

Despite the lengthy time required to complete tasks, this patient performed 44% of possible reaches with the affected arm. In ipsilateral space, all reaches were made with the affected arm, with the exception of one reach in task 1 by the unaffected hand. At midline, the patient used the affected arm for one repetition of task 2 and 3.

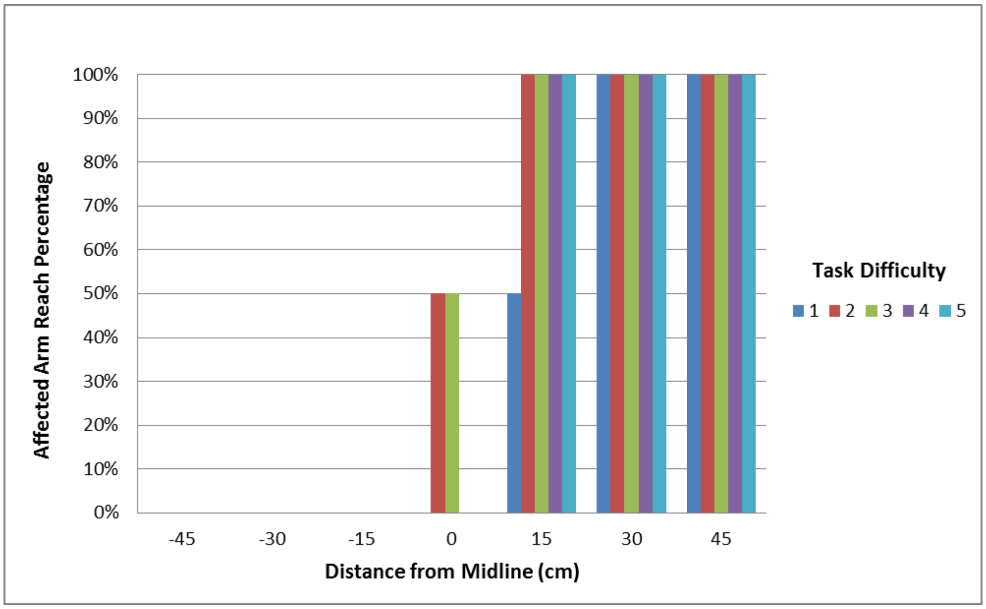


Figure 24: Reaching profile for patient 6 shows the affected arm reach percentage at each task location and for each level of task difficulty. All except one reach in ipsilateral space was performed with the affected, and a few reaches at midline.

Movement Time

Two-way ANOVA revealed a significant main effect of hand {$F(1,44) = 15.58$, $p<0.01$} but not task {$F(3,44) = 1.49$, $p=0.23$} nor was there interaction between hand and task {$F(3,44) = 0.50$, $p=0.682$}. Qualitatively, although there was no significant effect of task on movement time, the affected arm performed the free versions of each task slightly faster compared to the fixed version of the same task. Interestingly, the times for task 4 were the fastest of all tasks, which was not a trend observed in other patients. The most atypical result was the increase in MT1 from fixed to free versions of the task, and a consequent decrease in MT2.

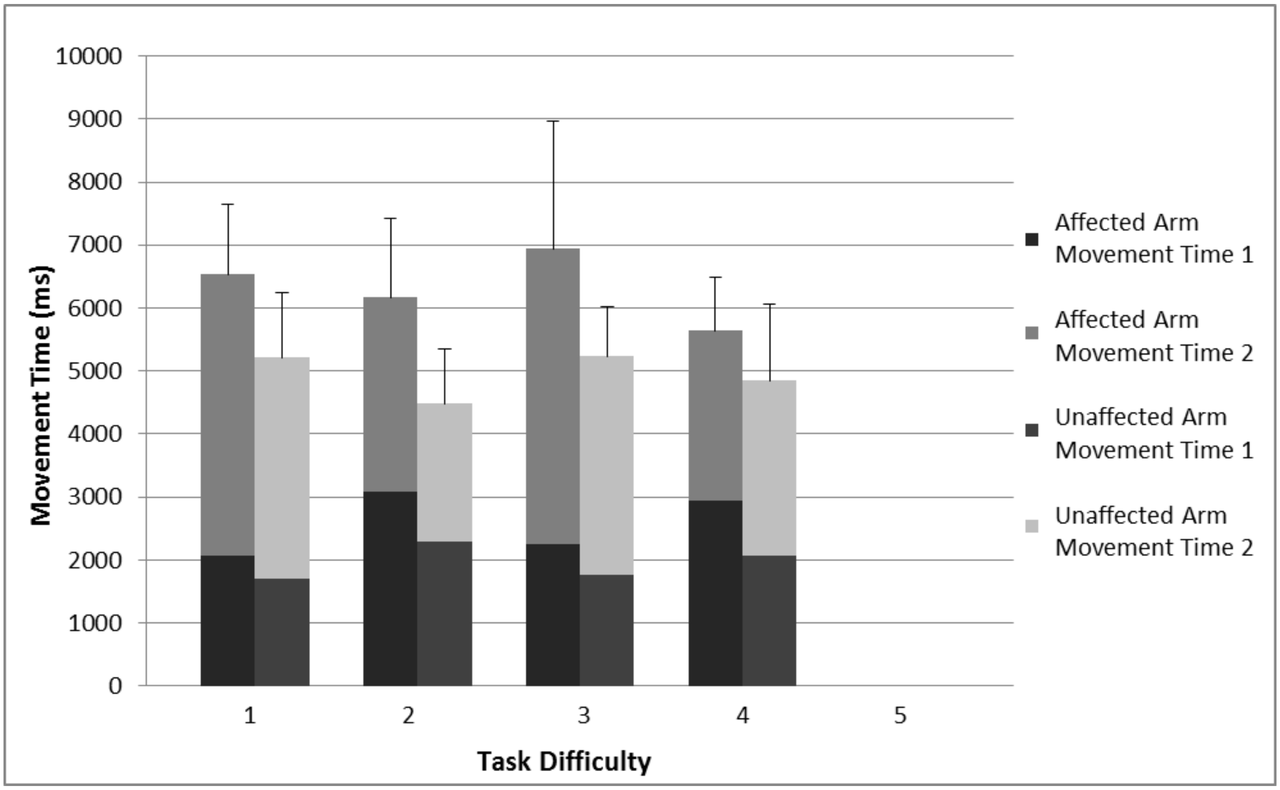


Figure 25: Task difficulty and movement time for the affected and unaffected arm of patient 6. The darker area of the bars represents movement time one, and lighter areas movement time two. Reaches with the affected arm were significantly slower than that unaffected (p<0.05). Standard error bars for total movement time are attached.

Peak Trunk Acceleration

Two-way ANOVA revealed a significant main effect of task {F(3,44) = 28, p<0.001}, but not hand {F(1,44) = 3.13, p=0.083} nor was there an interaction between task and hand {F(3,44) = .21, p=0.889}. Post-hoc Tukey's test indicated that peak trunk acceleration values for tasks 3 and 4 were significantly greater than for tasks 1 and 2 (p<0.001). Neither of the fixed or free versions of each task were significantly different from each other (p>0.05). Qualitatively, peak acceleration was greater for affected reaches than unaffected, but this was a minimal difference with an overall average of 0.117g during affected arm reaches and 0.103g during unaffected.

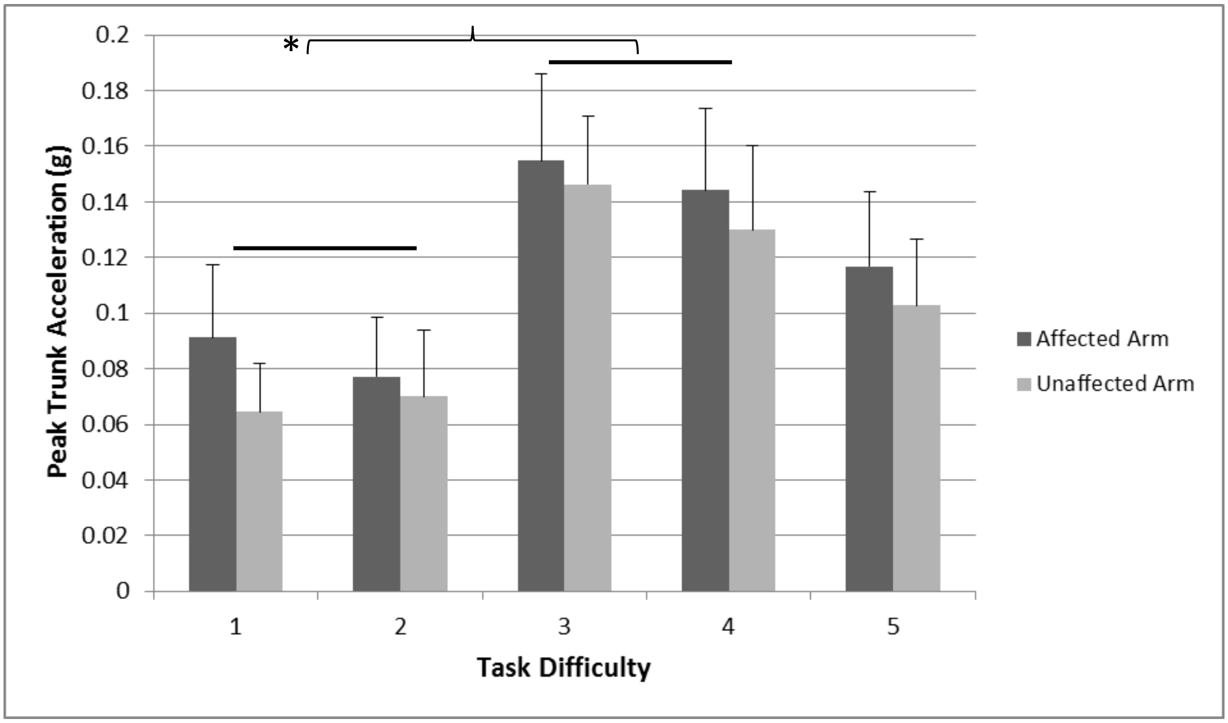


Figure 26: Task difficulty and peak trunk acceleration during affected and unaffected arm reaches for patient 6. Peak trunk acceleration was significantly greater for tasks 3 and 4 than tasks 1 and 2 ($p<0.05$). Bars represent means with standard error.

7.6.4 Patient 7

This patient's non-dominant side was affected with CMSA scores of 4 for arm and 5 for hand. Motor ataxia was present as well as a slight increase in muscle tone at the wrist (Ashworth 1) and elbow (1+). This patient was also tested in study 1 and had performed all reaches with the affected (pre-stroke dominant) arm, compared to the 43% affected arm reach percentage for the current visit. In the previous visit, the patient had scored 3 for arm and 6 for hand on the CMSA, which changed to 4 for arm and 5 for hand this visit. The majority of midline reaches were made by the affected limb and two contralateral reaches were made with the affected limb (both for task 1). The patient also made contralateral reaches with the unaffected (non-dominant) arm for tasks 1, 3 and 5. Of note is the patient's pre-stroke degree of hand dominance, which was scored as 7 (Bryden) and 17 (Waterloo Handedness Questionnaire), which are much lower scores than the majority of patients. The patient indicated that she was ambidextrous, as she was born left-handed but forced to use her right hand in school and therefore used either hand interchangeably (pre-stroke). This patient also made 3 switches, all from the affected (dominant) arm to the unaffected (non-dominant) arm. The switches occurred for tasks 1, 2 and 5 at -45cm (most contralateral with respect to affected arm), -15cm, and +15cm respectively.

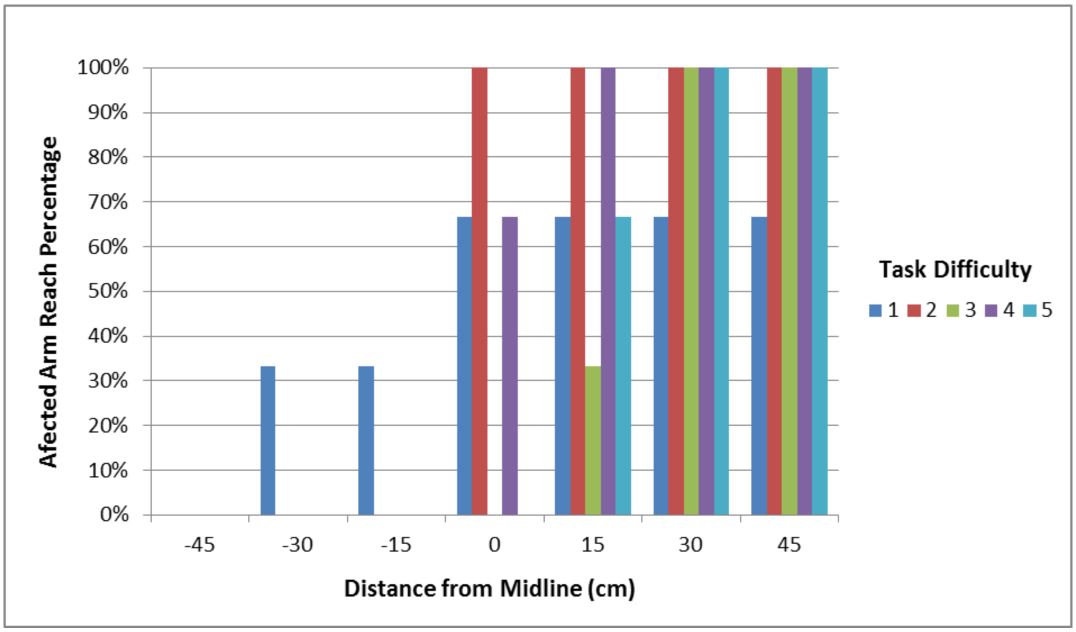


Figure 27: Reaching profile for patient 7 shows the affected arm reach percentage at each task location for each level of task difficulty. A majority of ipsilateral and midline reaches were performed with the affected arm, as well as a few contralateral reaches for task 1.

Movement Time

Two-way ANOVA revealed a significant main effect of hand, {$F(1,69) = 90.28$, $p<0.001$}, and task {$F(4,69) = 30.81$, $p<0.001$}, but no interaction between hand and task {$F(4,69) = 1.81$, $p=0.136$}. Post-hoc Tukey's test indicated that task 2 was significantly faster than all tasks except task 1 ($p<0.01$), and task 5 was significantly slower than all tasks ($p<0.001$).

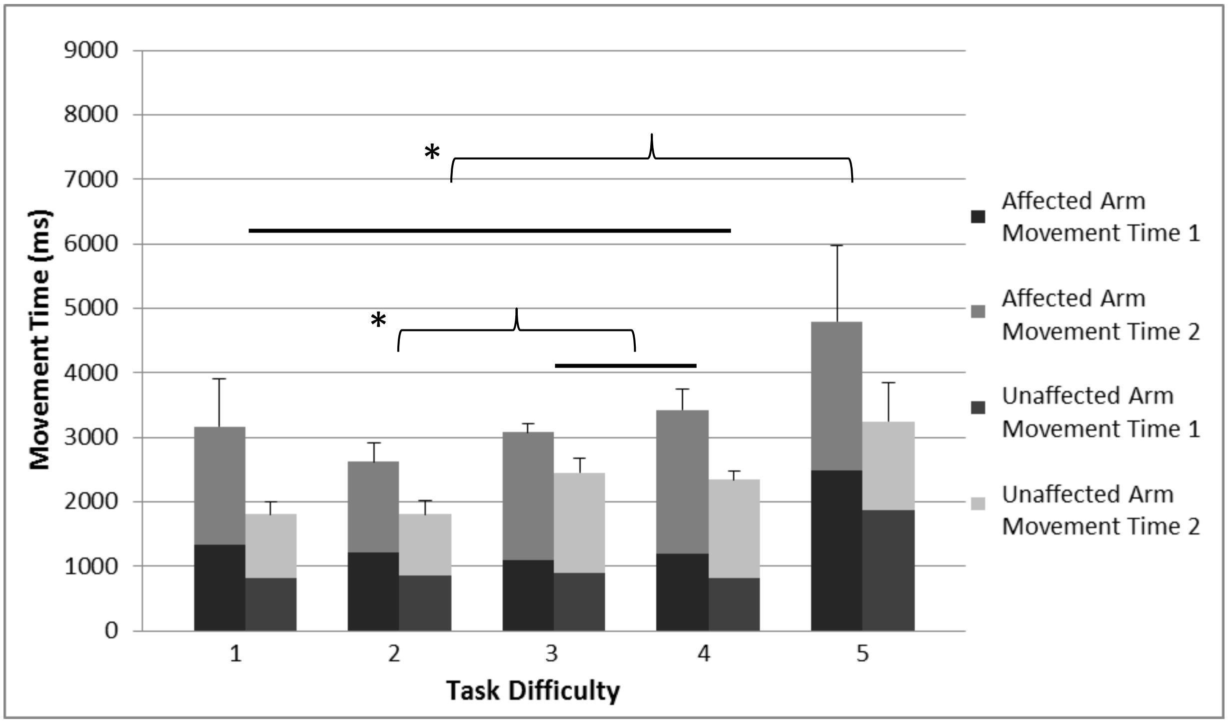


Figure 28: Task difficulty and movement time for the affected and unaffected arm of patient 7. The darker area of the bars represents movement time one, and lighter areas movement time two. Reaches with the affected arm were significantly slower than the unaffected (p<0.001). Task 2 was significantly faster than tasks 3, 4 and 5 (p<0.01), and task 5 was significantly slower than all tasks (p<0.001). Standard error bars for total movement time are attached.

Peak Trunk Acceleration

Two-way ANOVA revealed a significant main effect of hand {F(1,69) = 79.22, p<.001}, and task {F(4,69) = 6.37, p<.01}, but no interaction between hand and task {F(4,69) = .92, p=.455}. Post-hoc Tukey's test indicated that trunk acceleration for 3 was significantly greater than all other tasks (p<0.05). Qualitatively, there was some interaction between task and hand as the gap between peak acceleration during affected and unaffected reaches was much greater for the reach tasks (tasks 1 and 2) than for the grasping and fine control tasks.

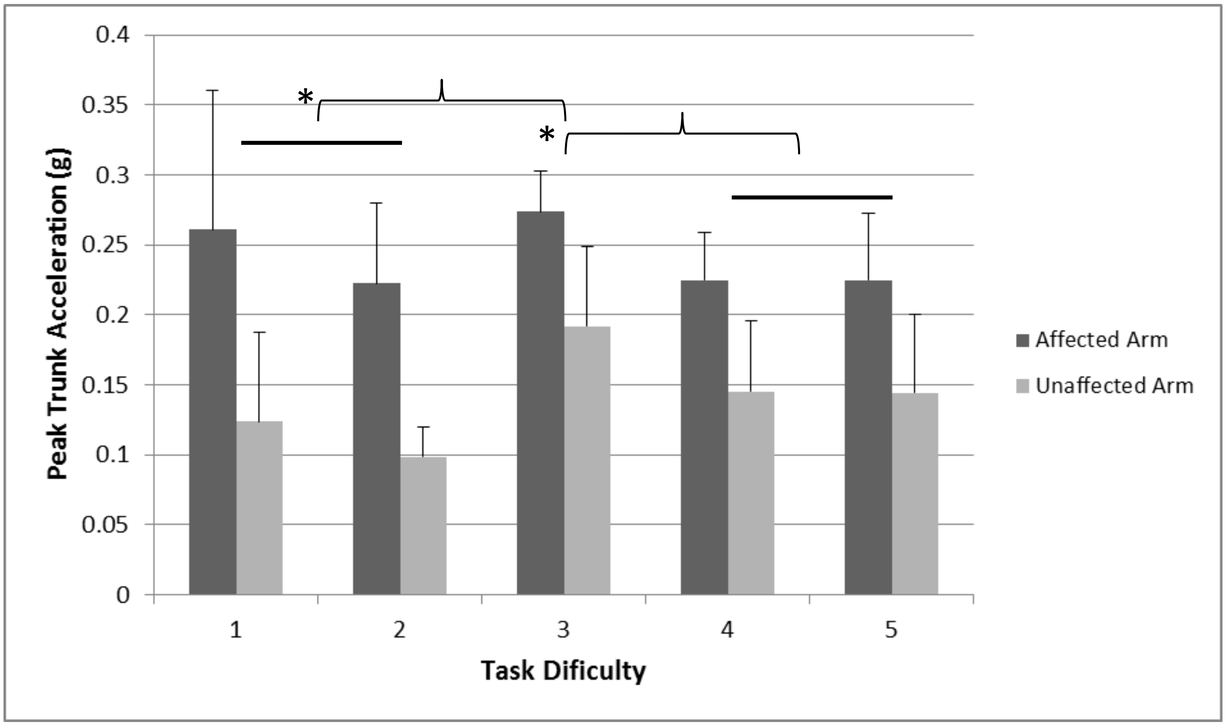


Figure 29: Task difficulty and peak trunk acceleration during affected and unaffected reaches for patient 7. Peak trunk acceleration was significantly greater during affected arm reaches (p<0.001). Acceleration was greater for task 3 compared to all other tasks (p<0.05). Bars represent means with standard error.

7.6.5 Patient 8

Patient 8 had their dominant side affected and had CMSA scores of 4 for arm and 5 for hand. This patient had the highest affected arm reach percentage (61%) of all patients, as well as the highest score for degree of pre-stroke hand dominance according to the Waterloo Handedness Questionnaire (24) in the DA group. In ipsilateral space, this patient performed 100% of possible reaches with the affected arm, and also performed all but one reach (for task 3) at midline. At the closest contralateral position, four reaches were made with the affected arm for task 1 (one), task 2 (one) and task 4 (two reaches).

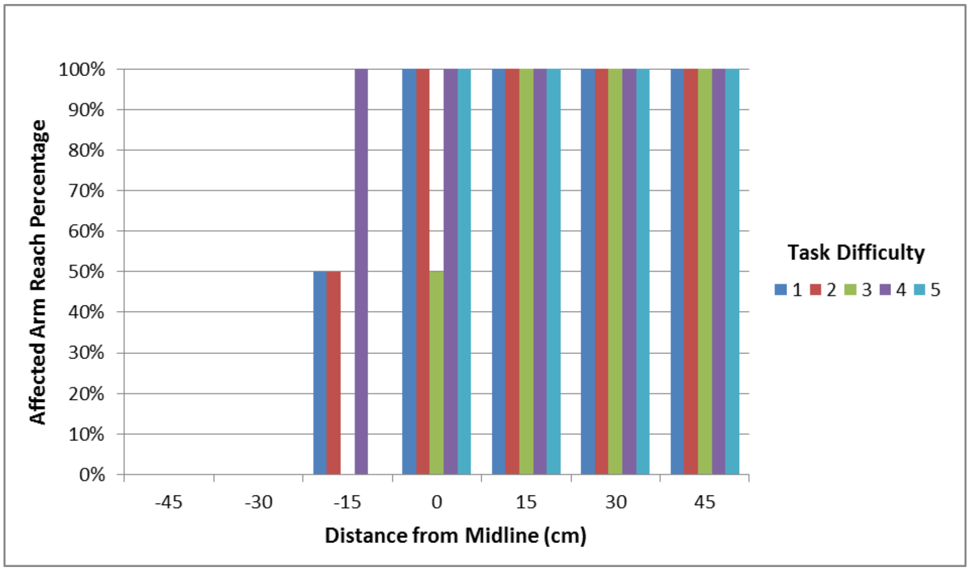


Figure 30: Reaching profile for patient 8 shows the affected arm reach percentage at each task location for each level of task difficulty. A maximum of affected arm reaches was performed in ipsilateral space, almost all reaches at midline as well as contralateral reaches for tasks 1, 2 and 4.

Movement Time

Two-way ANOVA revealed a significant effect of task {$F(4,50) = 31.87$, $p < 0.001$}, an effect of hand {$F(1,50) = 35.45$, $p < 0.001$} and an interaction between task and hand {$F(4,50) = 12.22$, $p < 0.001$}. Further analyses indicated that the only effect of task or hand was due to the doubling in movement time for task 5 that occurred for the affected but not the unaffected arm.

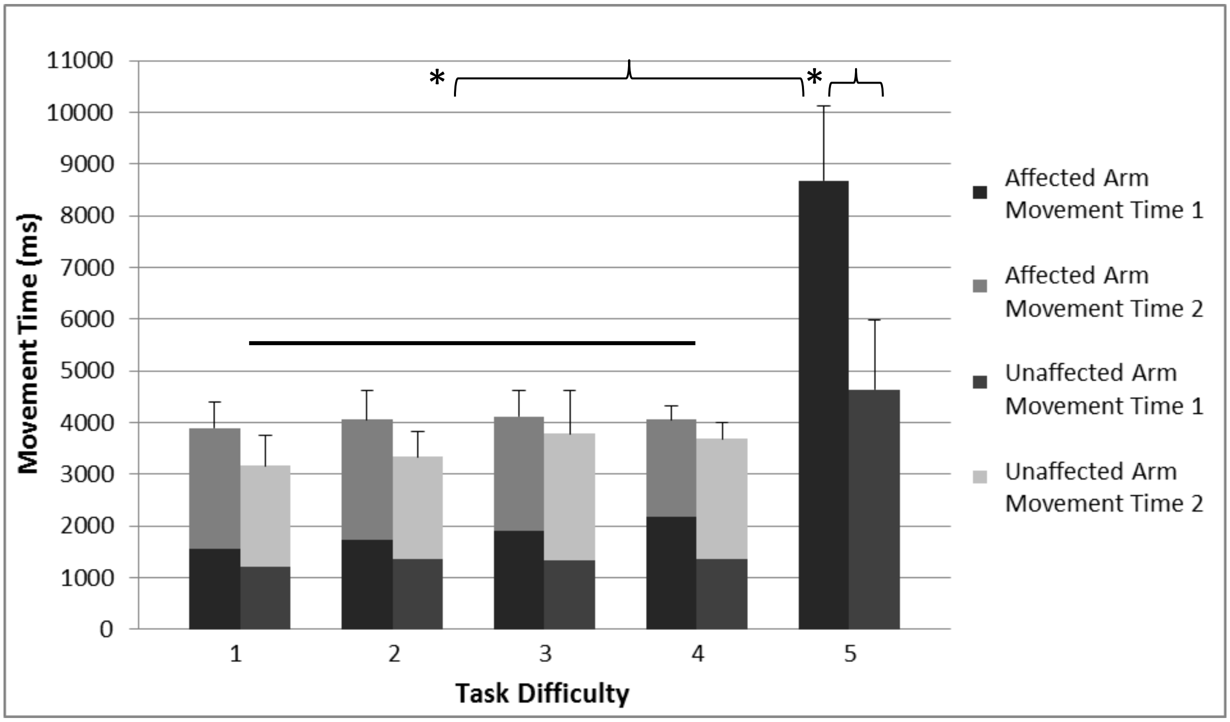


Figure 31: Task difficulty and movement time for the affected and unaffected arm of patient 8. The darker area of the bars represents movement time one, and lighter areas movement time two. Task 5 was significantly slower than all other tasks for affected reaches only (p<0.05).

Peak Trunk Acceleration

Two-way ANOVA indicated no effect of task {F(4,50) = 1.75, p = 0.151}, or hand {F(1,50) = 0.01, p = 0.910} or an interaction between task and hand {F(4,50) = 0.92, p = 0.458}. Qualitatively, trunk values for the affected arm were higher for the fixed version of the reach and the grasp tasks, decreasing for free reach and repeating this pattern for the grasping tasks.

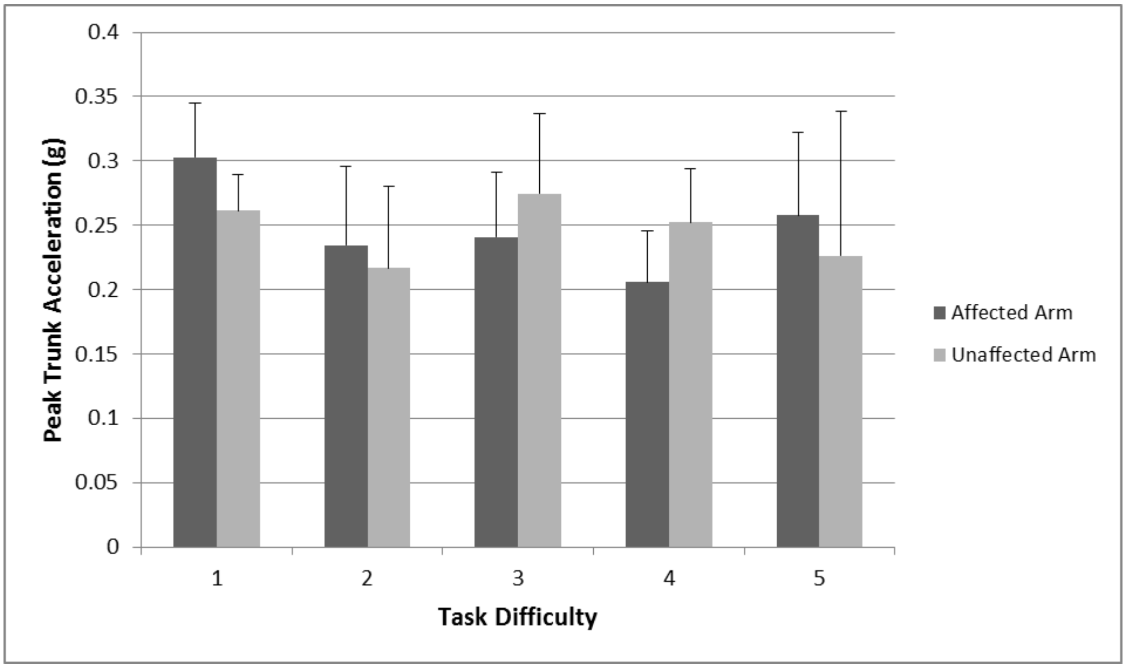


Figure 32: Task difficulty and peak trunk acceleration during affected and unaffected reaches for patient 8. There was no effect of arm or task difficulty on peak trunk acceleration. Bars represent means with standard error.

7.6.6 Patient 9:

This patient's dominant arm was affected, with CMSA scores of 5 for both arm and hand. A slight increase in muscle tone was observed at the wrist and elbow (Ashworth of 1), and this patient had a CMSA score of 4 for postural control, the lowest of any patients in the moderate or mild impairment group. Shoulder pain was absent; however, at least one prognostic indicator was present. Interestingly, all trials at midline for task 5 were performed with the affected arm, as well as one trial in contralateral space; however, the affected arm performed only 2/3 reaches for task 5 at each position in ipsilateral space. For the first four tasks, the affected arm completed 100% of reaches in ipsilateral space, as well as performing 3 different tasks at midline (tasks 1, 3 and 5) for an overall affected arm reach percentage of 49%.

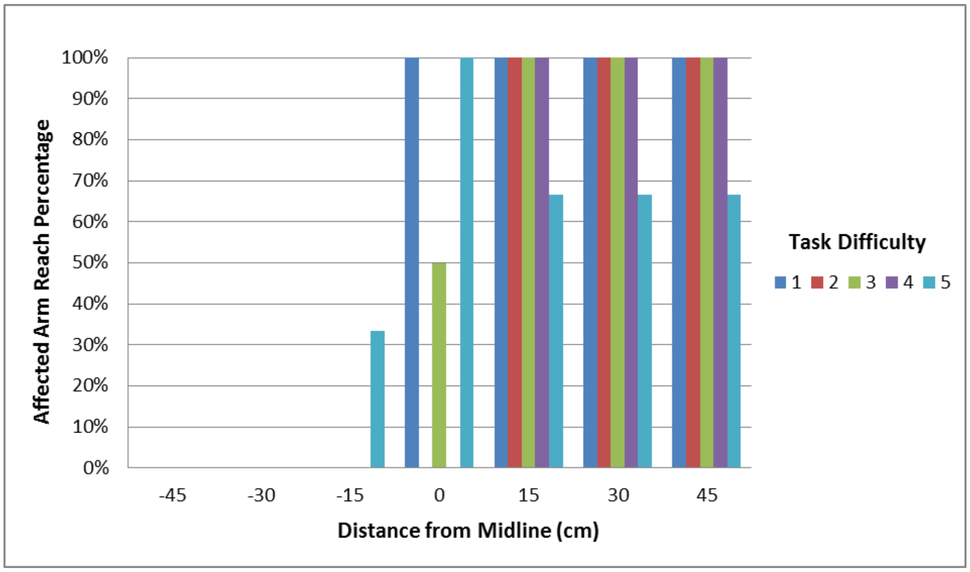


Figure 33: Reaching profile for patient 9 shows the affected arm reach percentage at each task location for each level of task difficulty. The affected arm was used to complete all tasks in ipsilateral space, except for a few repetitions of task 5. Tasks 1 and 5 were performed to a maximum at midline and there was also one contralateral reach with the affected arm for task 5.

Movement time

Two-way ANOVA revealed a significant effect of task $\{F(4,63) = 93.87, p<0.001\}$ and hand $\{F(1,63) = 31.24, p<0.001\}$ and an interaction between task and hand $\{F(4,63) = 4.64, p < 0.005\}$. Post-hoc analysis indicated that the only effect of task or hand was observed for task 5 ($p<.001$), as movement time increased significantly for both hands compared to all other tasks; however, the affected arm took significantly longer for task 5 than the unaffected arm.

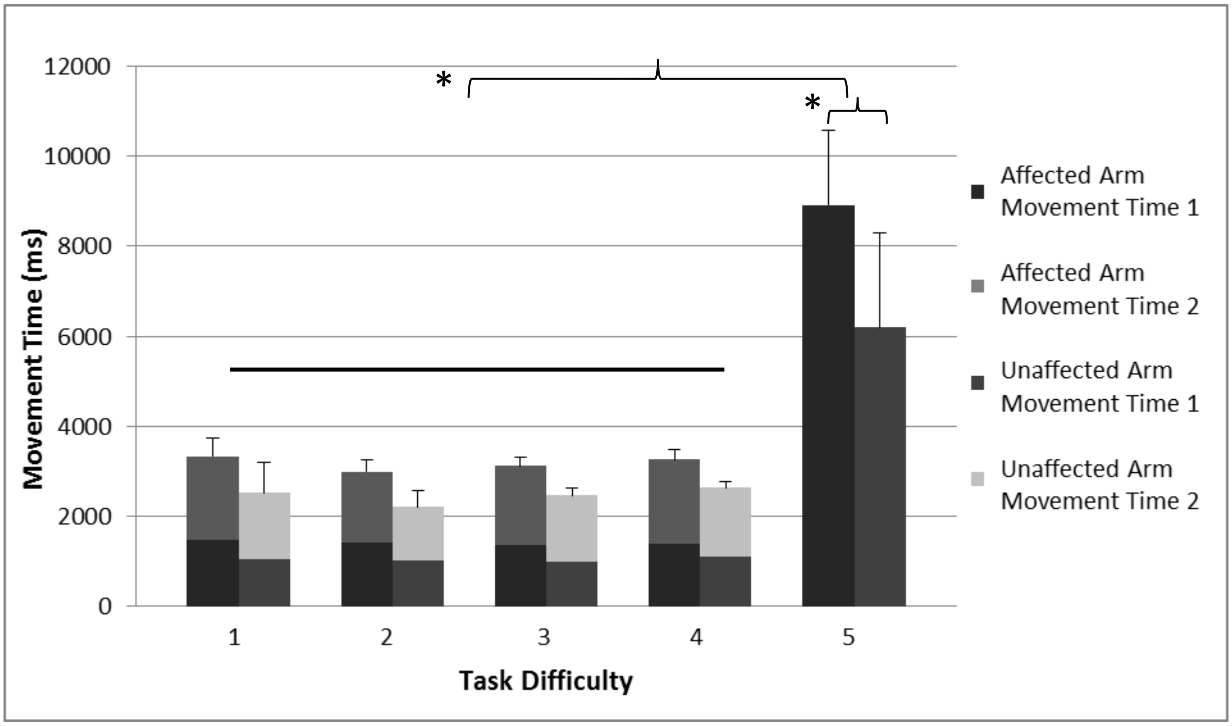


Figure 34: Task difficulty and movement time for the affected and unaffected arm of patient 9. The darker area of the bars represents movement time one, and lighter areas movement time two. Reaches with the affected arm were significantly slower than the unaffected for task 5 only ($p<0.05$). Task 5 was significantly slower than all other tasks ($p<0.05$).

Peak Trunk Acceleration

Two-way ANOVA revealed a significant effect of task {$F(1,63) = 95.77$, $p<0.001$}, and hand {$F(4,63) = 28.7$, $p <0.001$}; and an interaction between task and hand {$F(4,63) = 4.64$, $p<0.001$}. Post-hoc analysis indicated that peak trunk acceleration was significantly greater for affected arm reaches in tasks 1 through 3 ($p<0.05$), but not tasks 4 and 5.

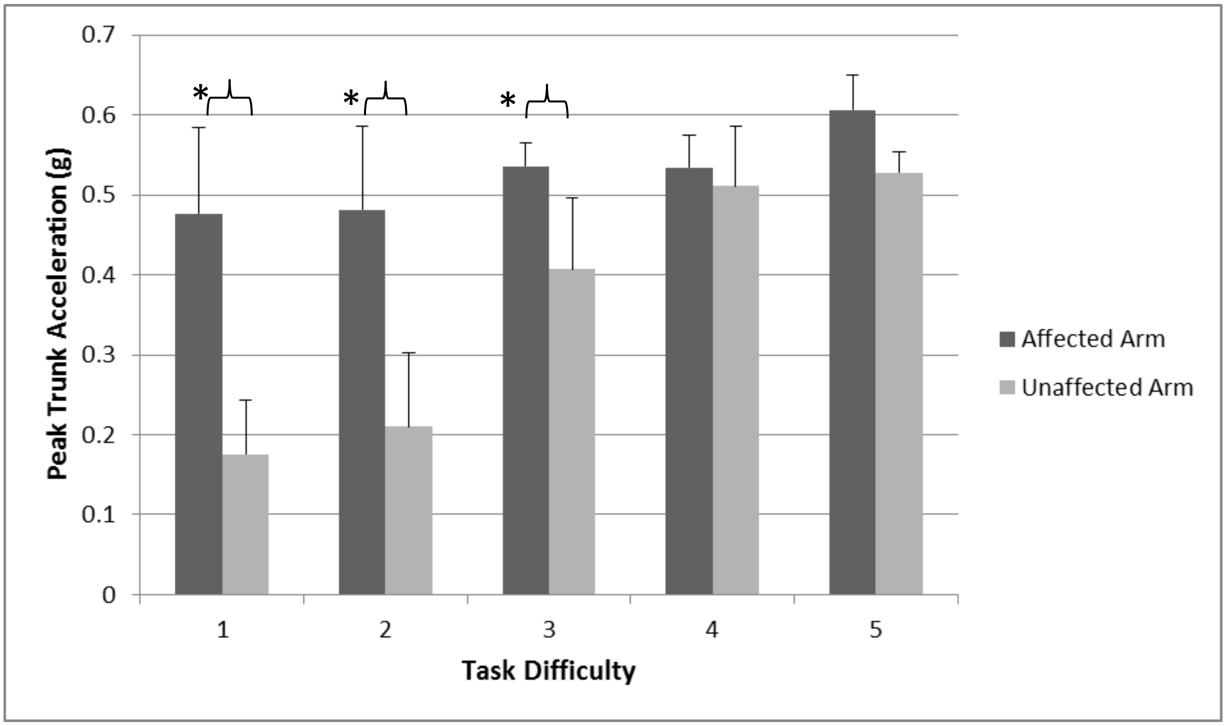


Figure 35: Task difficulty and peak trunk acceleration during affected and unaffected reaches for patient 9. Peak trunk acceleration was significantly greater during affected arm reaches compared to unaffected reaches for tasks 1 to 3 ($p<0.05$). Bars represent means with standard error.

7.7 Case Descriptions: Mild Impairment Group

7.7.1 Patient 10:

Patient 10 had their non-dominant side affected with CMSA scores of 6 for arm and 7 for hand. Mild ataxia in the upper limb was present, as well as moderate shoulder pain. Patient 10 had an overall affected arm reach percentage of 44%, and performed all reaches in ipsilateral space with the affected arm, except for two reaches made with the unaffected arm for task 5. At midline, this patient performed one reach with the affected arm for tasks 1 through 3.

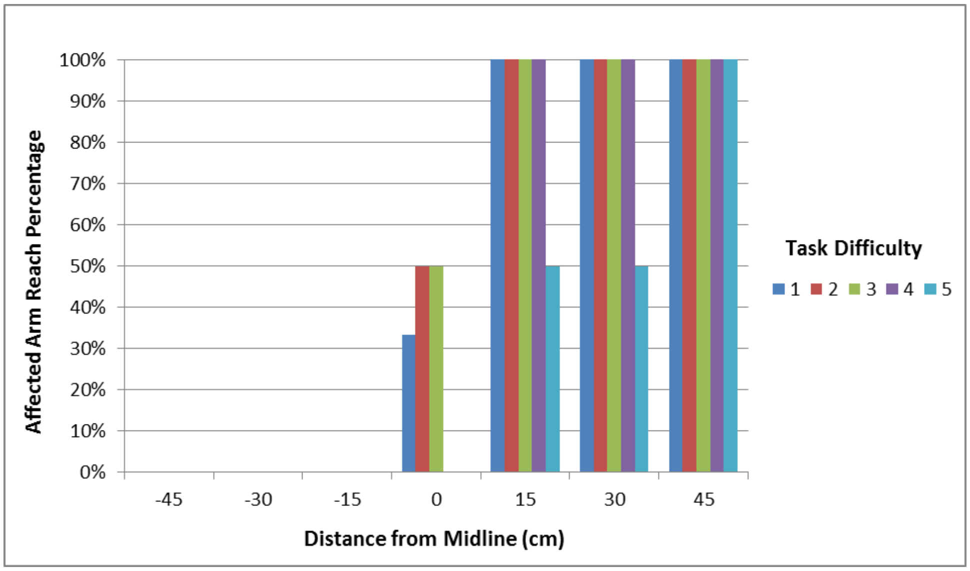


Figure 36: Reaching profile for patient 10 shows the affected arm reach percentage at each task location for each level of task difficulty. The affected arm was used to complete all tasks in ipsilateral space, except for a few repetitions of task 5. The affected arm also completed reaches for the three easiest tasks at midline.

Movement Time

Two-way ANOVA revealed a significant effect of task {$F(4,51) = 372.99$ $p<0.001$} and hand {$F(1,51) = 383.71$, $p<0.001$} and an interaction between task and hand {$F(4,51) = 166.40$, $p < 0.001$}. Post-hoc analysis indicated that the only significant difference due to task or hand was observed for task 5 ($p<0.001$), where the unaffected hand did not have a significant increase in movement time but the affected arm movement time doubled.

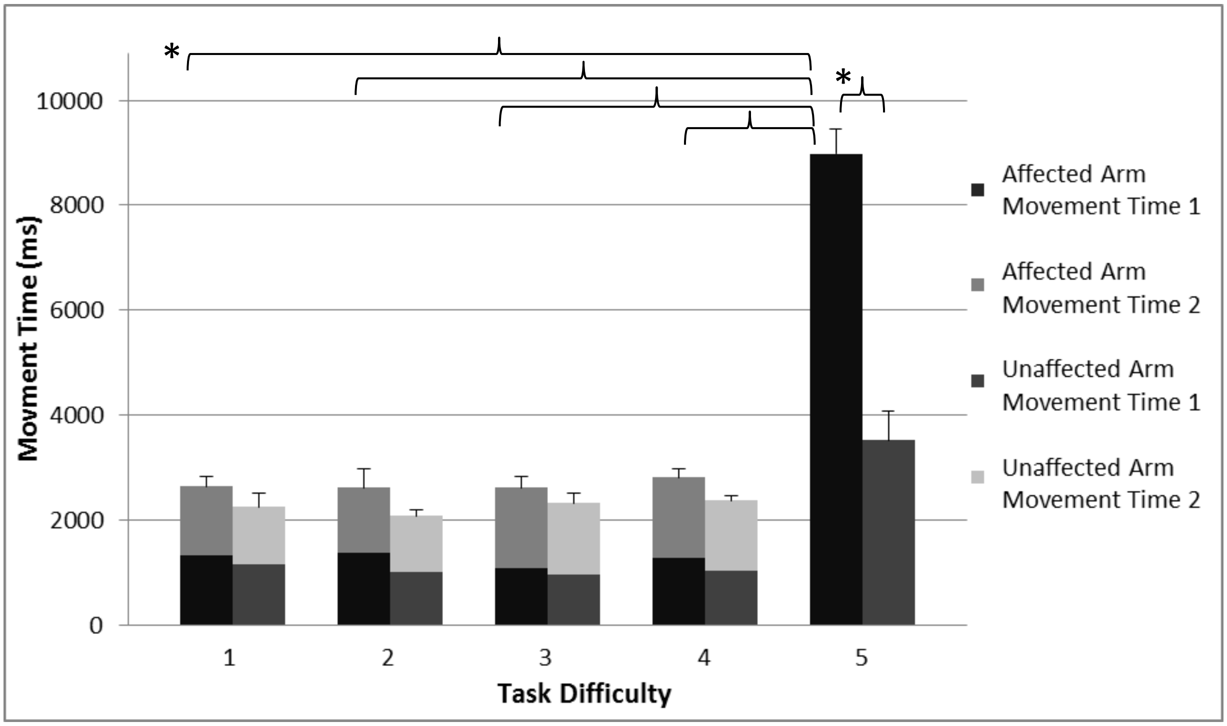


Figure 37: Task difficulty and movement time for the affected and unaffected arm of patient 10. The darker area of the bars represents movement time one, and lighter areas movement time two. Reaches with the affected arm were significantly slower than the unaffected for task 5 only (p<0.001). Task 5 with the affected arm was significantly slower than all other reaches with the affected or unaffected arm (p<0.001).

Peak Trunk Acceleration

Peak trunk acceleration was significantly greater for affected arm reaches, as revealed by two-way ANOVA {F(1,51) = 95.55, p<0.001}, and approached significance for the effect of task {F(4,51) = 2.33, p = 0.068}; however, there was no interaction between task and hand {F(4,51) = 0.91, p = 0.467}.

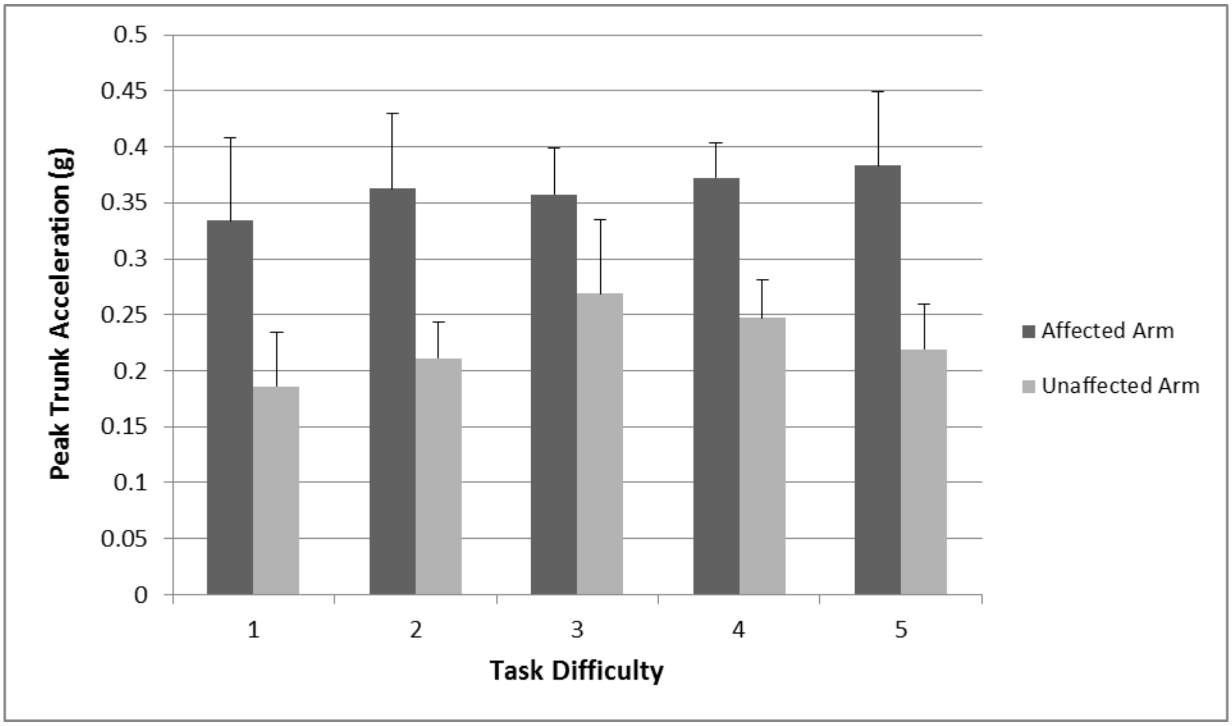


Figure 38: Task difficulty and peak trunk acceleration during affected and unaffected reaches for patient 11. Peak trunk acceleration was significantly greater during affected arm reaches than unaffected ($p<0.05$). Bars represent means with standard error.

7.7.2 Patient 11:

This patient's non-dominant arm was affected, with CMSA scores of 6 for arm and 7 for hand. Mild sensory loss was present, shoulder pain was absent; however, at least one prognostic indicator was present. Overall affected arm reach percentage was 46%. In ipsilateral space, all reaches were performed with the affected arm, 2 reaches were made at midline (task 2 and task 4), and no affected arm reaches were made in contralateral space. This patient also made one switch in the space contralateral to the affected arm; after initiating the reach with the affected arm they switched to the unaffected arm to execute task 3.

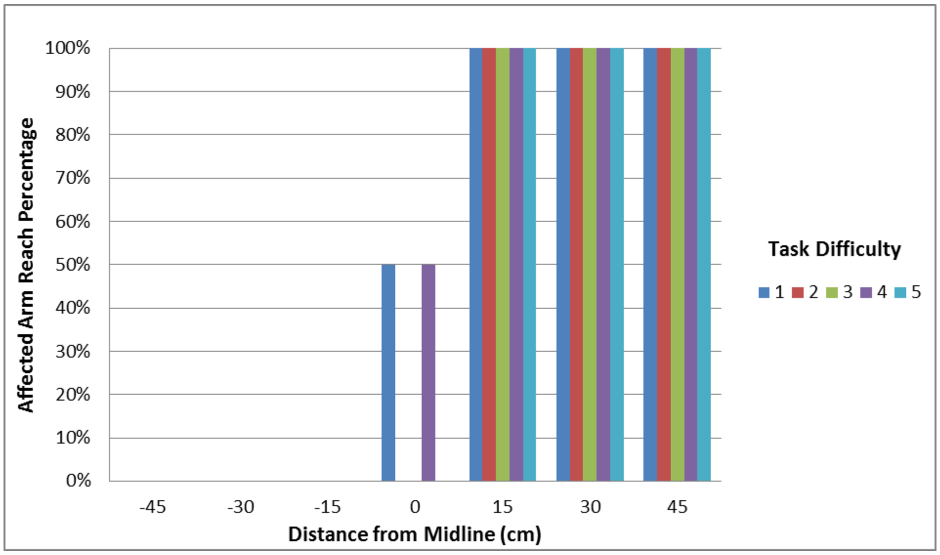


Figure 39: Reaching profile for patient 11 shows the affected arm reach percentage at each task location for each level of task difficulty. The affected arm completed a maximum of reaches in ipsilateral space and a few reaches at midline for tasks 1 and 3.

Movement Time

Two-way ANOVA indicated that there was a main effect of task {$F(4,47) = 128.63$, $p<0.001$}, no significant effect of hand {$F(1,47) = 0.03$, $p = 0.87$} and no interaction between task and hand {F(4,47 = 0.25, $p = 0.906$}. Post-hoc Tukey's test revealed a significant increase in movement time for task 3, compared to tasks 1 and 2, as well the movement times for both arms were significantly greater in task 5 than all other tasks.

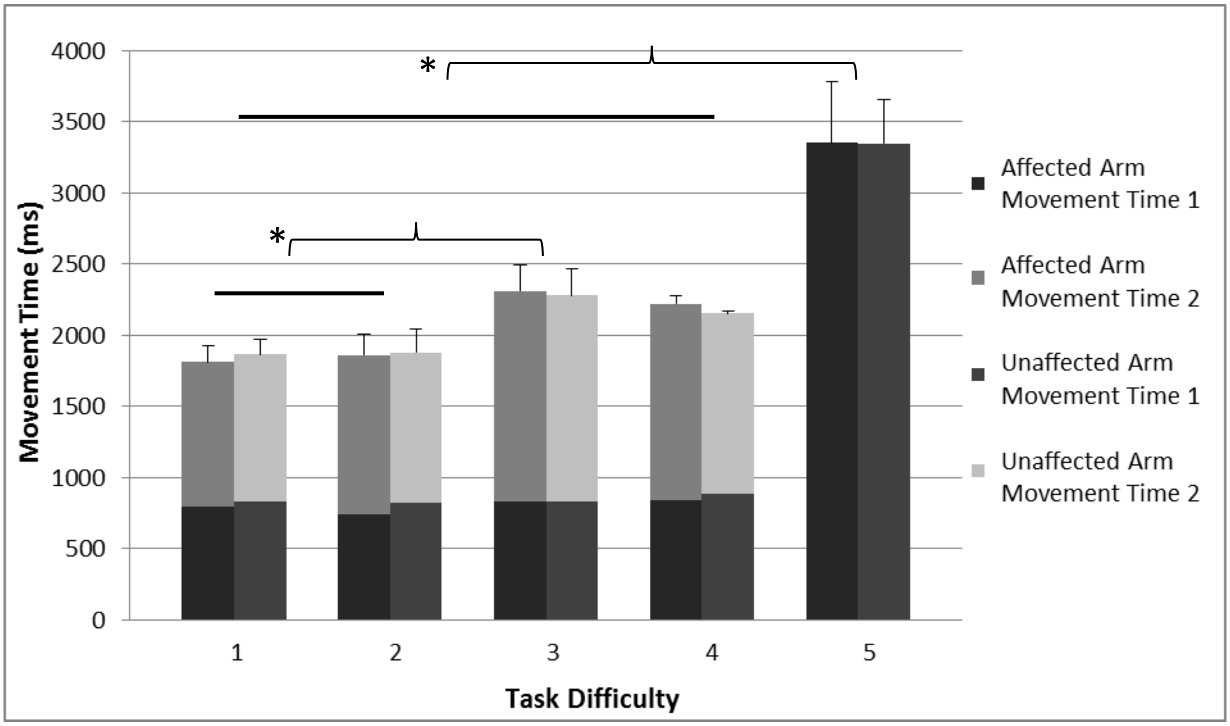


Figure 40: Task difficulty and movement time for the affected and unaffected arm of patient 11. The darker area of the bars represents movement time one, and lighter areas movement time two. Movement times were not significantly different between affected and unaffected arms. Movement time was significantly slower in task 3 compared to tasks 1 and 2, and task 5 was significantly slower than all tasks.

Peak Trunk Acceleration

Two-way ANOVA revealed an effect of task {$F(3,37) = 9.44$, $p<0.05$}, an effect of hand {$F(1,37) = 5.64$, $p <0.05$} but no interaction between task and hand {$F(4,37) = 1.71$, $p = 0.182$}. Post-hoc analysis revealed that peak acceleration in task 1 was significantly lower than in tasks 2 and 3 ($p<0.05$).

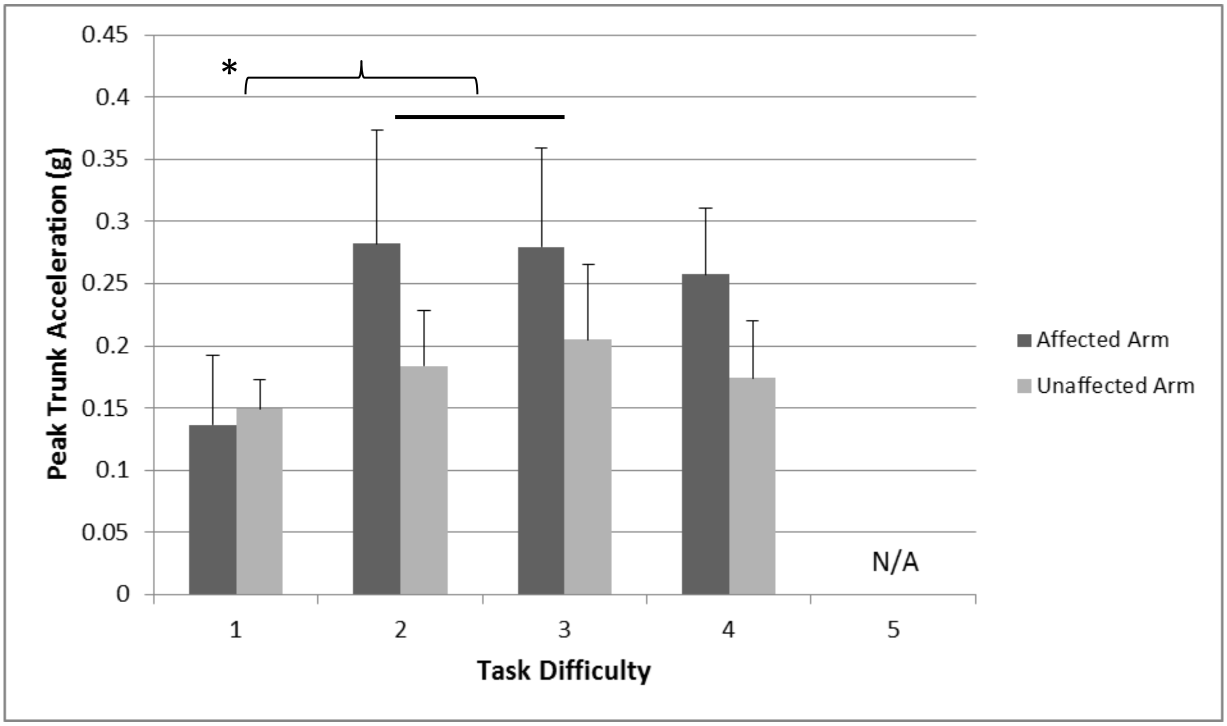


Figure 41: Task difficulty and peak trunk acceleration during affected and unaffected reaches for patient 11. Peak trunk acceleration was significantly greater during affected arm reaches than unaffected (p<0.05). Acceleration in task 1 was significantly lower than tasks 2 and 3 (p<0.05). Bars represent means with standard error.

7.7.3 Patient 12

This patient's non-dominant side was affected, with CMSA scores of 6 for arm and 7 for hand. Shoulder pain and all prognostic indicators were absent. Of note is that patient 12 was tested in study 1 and had performed all reaches with the dominant, unaffected limb despite the ability to successfully perform all tasks with the affected limb. At this visit, the patient had the same average CMSA score; however, he had previously scored 7 for arm and 6 for hand. In the current visit the patient had an affected arm reach percentage of 42% and performed all but one reach in ipsilateral space (task 5) with the affected arm. The affected arm was not used for any tasks at midline or in contralateral space. This patient performed five switches, all occurring after initiating the reach with the unaffected (dominant) arm but executing the task with the affected (non-dominant) arm. Patient 12 made one switch each for tasks 1, 2 and 4 and two switches for task 5, all in contralateral space.

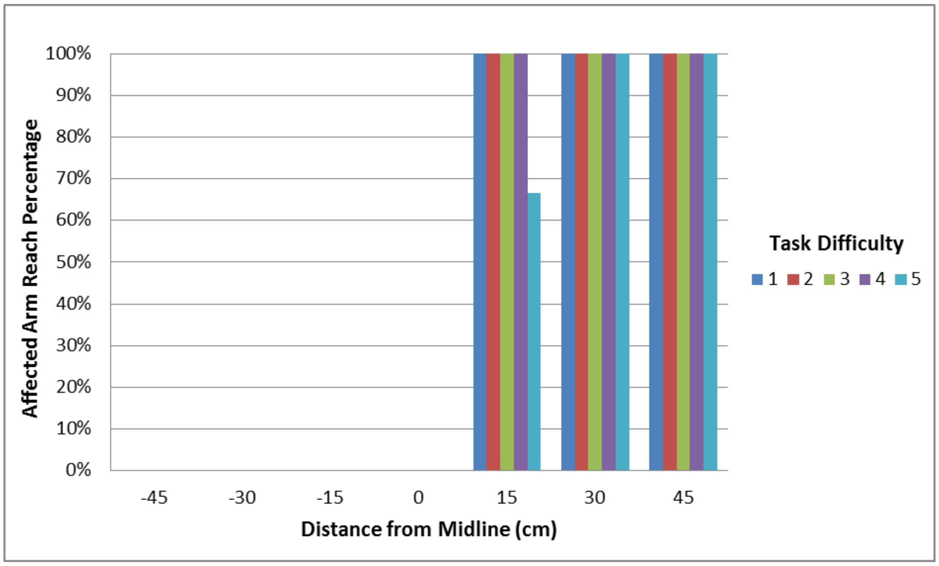


Figure 42: Reaching profile for patient 12 shows the affected arm reach percentage at each task location for each level of task difficulty. The affected arm completed a maximum of reaches in ipsilateral space only; all other reaches were completed with the unaffected arm.

Movement time

Two-way ANOVA revealed no significant effect of hand {$F(1,57) = 0.88$, $p = 0.383$}, and movement time values were actually faster (although not significantly), for the affected arm in task 5. There was a main effect of task {$F(4,57) = 52.83$, $p<0.001$}, but no interaction between hand and task {$F(4,57) = 1.44$, $p = 0.233$}. Post-hoc Tukey's test revealed significantly longer movement times for the tasks 3 and 4, compared to tasks 1 and 2 ($p<0.01$), as well task 5 took significantly longer than all other tasks ($p<0.0001$). However, there was no significant difference between the fixed and free versions of each task (i.e. between tasks 1 and 2, between 3 and 4).

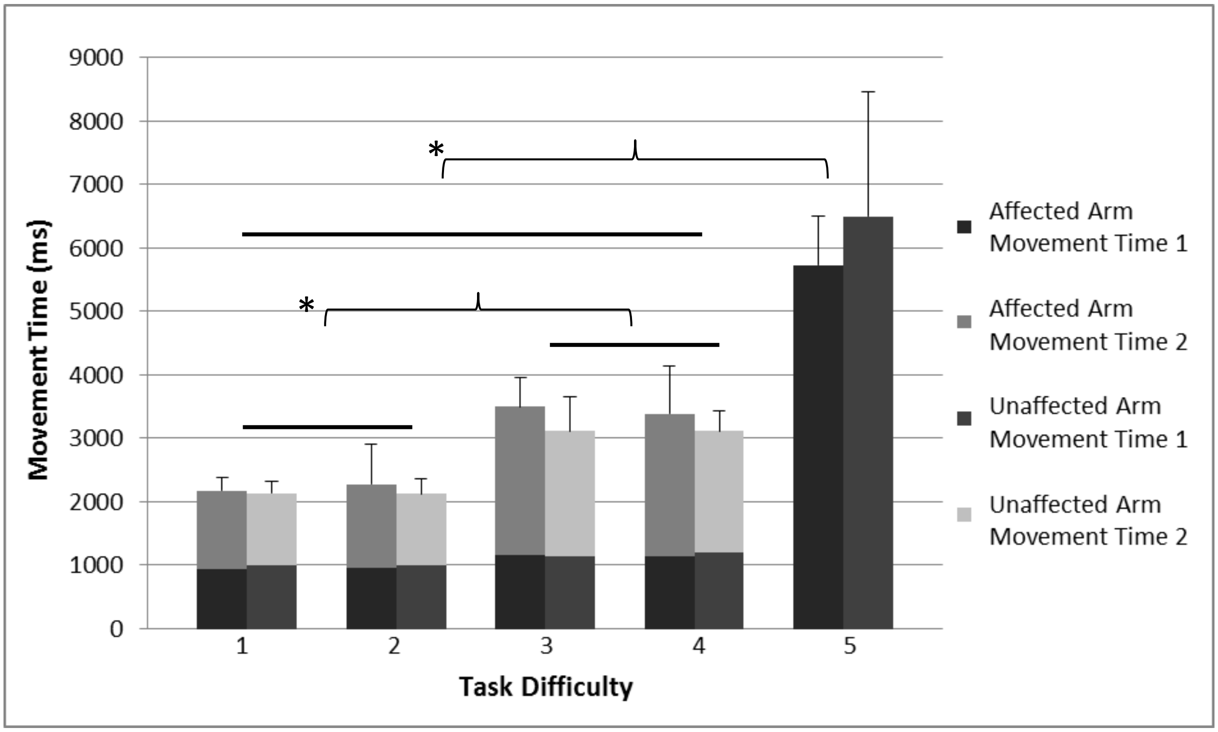


Figure 43: Task difficulty and movement time for the affected and unaffected arm of patient 12. The darker area of the bars represents movement time one, and lighter areas movement time two. Movement times were not significantly different between affected and unaffected arms. Movement time was significantly slower in tasks 3 and 4 compared to tasks 1 and 2, and task 5 was significantly slower than all tasks.

Peak Trunk Acceleration

Peak trunk acceleration was significantly affected by hand $\{F(1,57) = 4.7, p=0.0024\}$, and task $\{F(4,57) = 8.85, p = 0.0043\}$, but there was no interaction between hand and task $\{F(4,57) = 1.96, p = 0.113\}$. Post-hoc analyses revealed that trunk acceleration in task 3 was significantly greater than in task 1 ($p<0.01$) and almost significantly greater than task 2 ($p=0.077$). Qualitatively, average peak trunk acceleration during affected arm reaches (0.267g +/- 0.054) was higher compared to unaffected reaches (0.217g +/- 0.071), and was higher for every task except task 4.

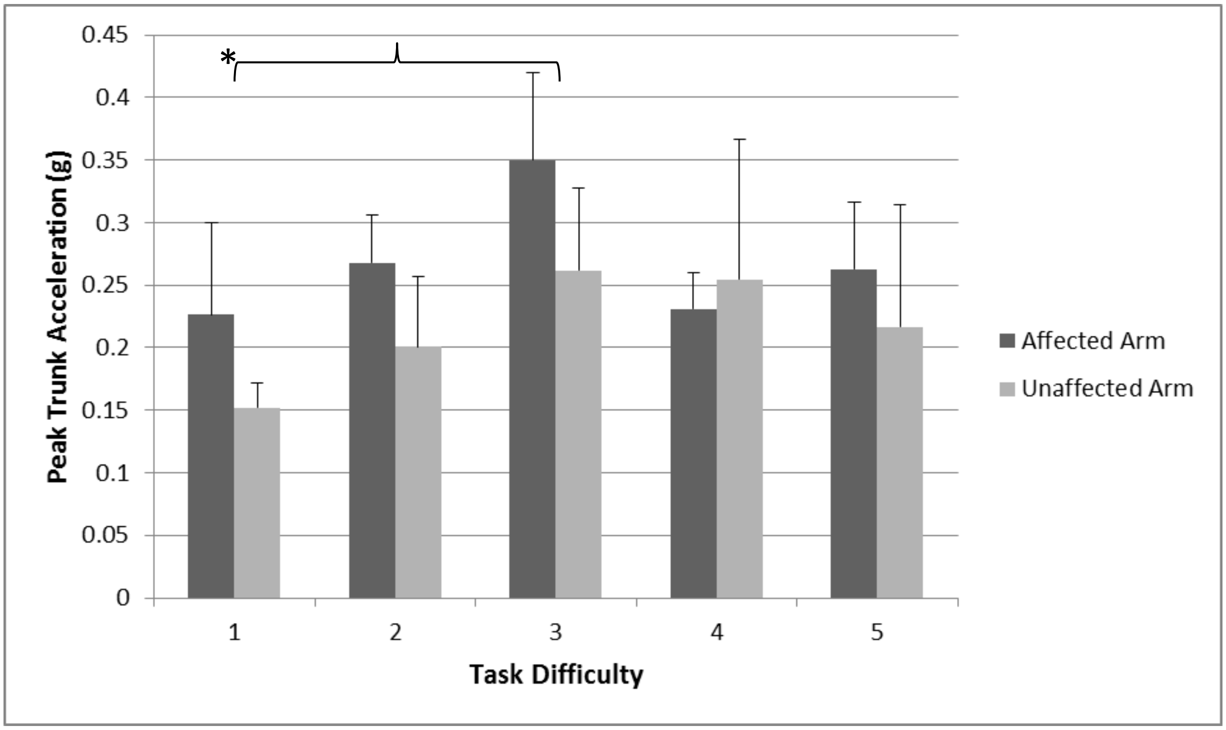


Figure 44: Task difficulty and peak trunk acceleration during affected and unaffected reaches for patient 10. Peak trunk acceleration was significantly greater during affected arm reaches than unaffected ($p<0.05$). Acceleration in task 3 was significantly greater than in task 1 ($p<0.01$). Bars represent means with standard error.

7.7.4 Patient 13

Patient 13 had their dominant side affected, with CMSA scores of 6 for both arm and hand. Shoulder pain was intermittent with pathology in just the shoulder. Affected arm reach percentage was 61%, one percent below the highest affected arm reach percentage for all patients. Patient 13 performed all repetitions of task 5 with the affected arm regardless of target location, despite taking 3 seconds longer to complete the task compared to other patients in the mild impairment group. At midline, this patient performed one reach for tasks 1 and 3, and in contralateral space made one reach for task 1. In ipsilateral space (with respect to the affected arm), the patient reached across with the unaffected arm for one trial in tasks 1 and 3.

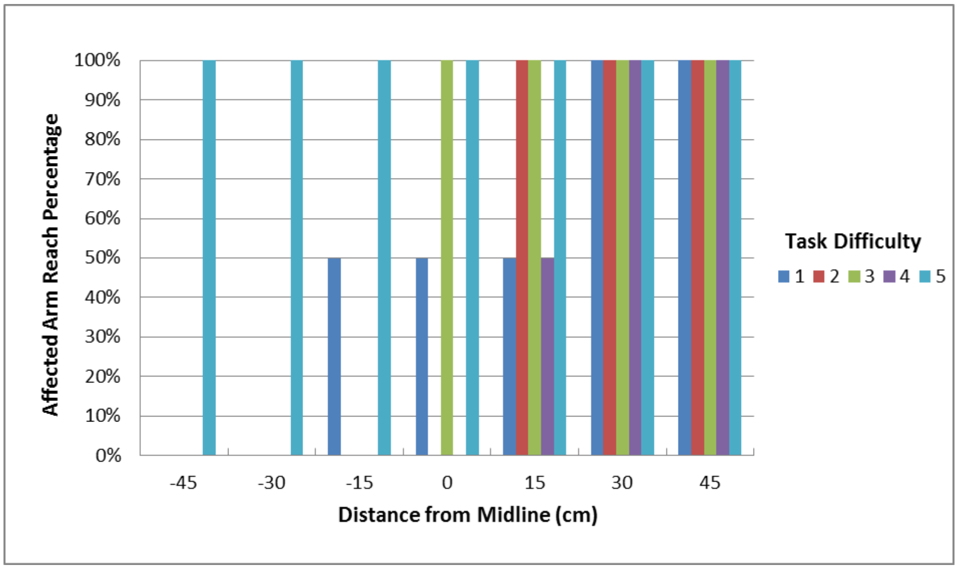


Figure 45: Reaching profile for patient 13 shows the affected arm reach percentage at each task location for each level of task difficulty. The affected arm performed almost all reaches in ipsilateral space, half of possible reaches at midline and completed all repetitions of task 5 regardless of location.

Movement time

Two-way ANOVA indicated a main effect of task {F(4,41) = 42.02, p<0.001} no effect of hand {F(1,41) = 0.32, p = 0.577} and no interaction between task and hand {F(4,41) = 0.22, p = 0.883}. Further analyses revealed that tasks 3 and 4 took significantly longer than task 1 (p<0.05), and were almost significantly longer than task 2 (p = 0.084). Task 5 was only performed by the affected arm, and took significantly longer than all other tasks (p<0.0001).

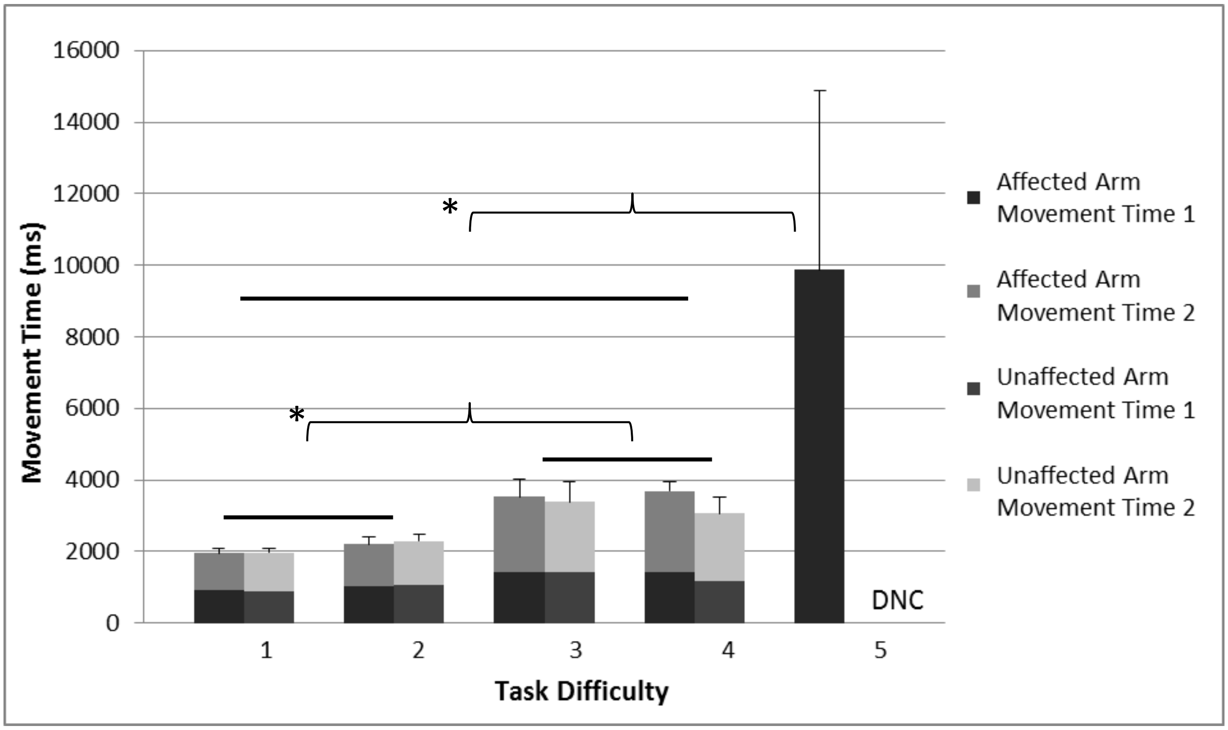


Figure 46: Task difficulty and movement time for the affected and unaffected arm of patient 13. The darker area of the bars represents movement time one, and lighter areas movement time two. Movement times were not significantly different between affected and unaffected arms. Movement time was significantly slower in tasks 3 and 4 compared to task 1, and task 5 was significantly slower than all tasks (only completed with the affected arm).

Peak Trunk Acceleration

Similar to movement time, two-way ANOVA indicated a main effect of task {$F(4,41) = 3.72$, $p<0.05$} but not hand {$F(1,41) = 1.29$, $p = 0.263$} or an interaction between task and hand {$F(4,41) = 0.39$, $p = 0.762$}. Further analyses revealed the only significant difference between tasks was a greater peak acceleration for task 4 compared to task 2. Although not significant, trunk values were actually lower during affected arm reaches for tasks 1 and 2, and were only slightly higher than the unaffected arm for tasks 3 and 4.

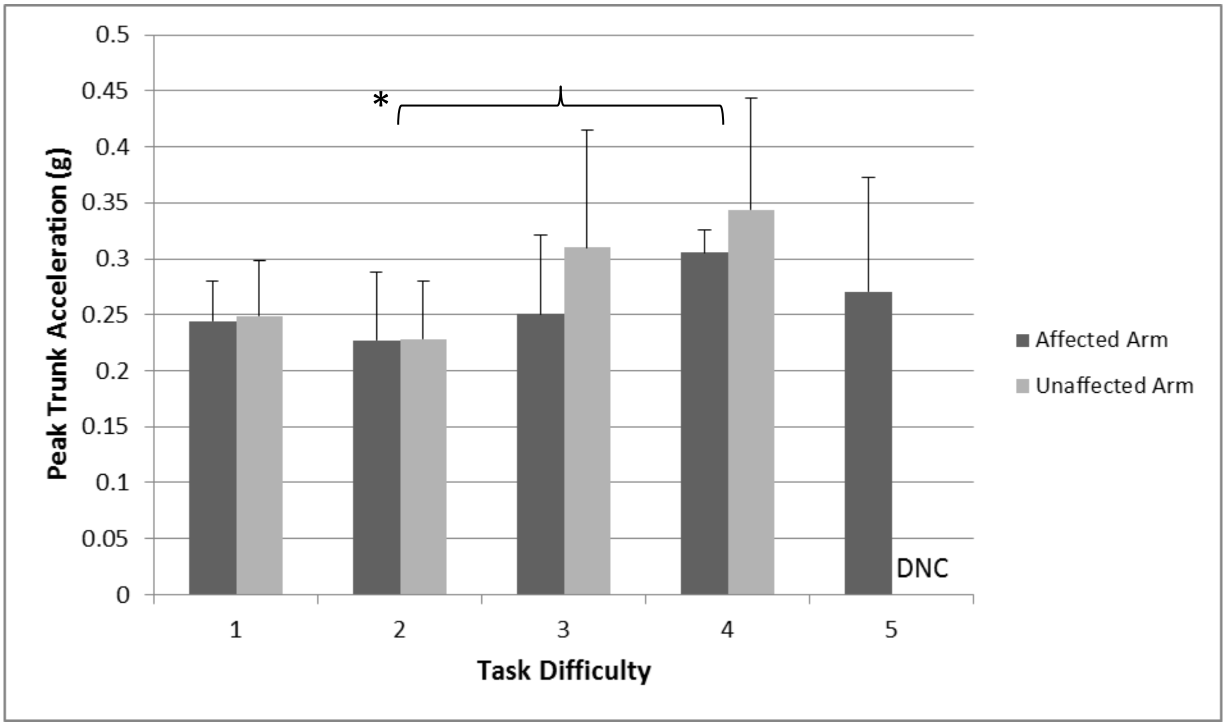


Figure 47: Task difficulty and peak trunk acceleration during affected and unaffected reaches for patient 13. Peak trunk acceleration was not significantly different between affected and unaffected reaches. The only effect of task was a significantly higher acceleration during task 4 compared to task 2.

7.8 Patient Summary

These case studies highlighted the individual differences in patient characteristics and kinematics that may have influenced task-specific preference. Despite the heterogeneity there were some patterns that emerged in the individual reach profiles for the 8 patients who could complete all 5 tasks with the affected arm and voluntarily chose to use this arm. Figure 48 shows a summary of all these individual reach profiles, which illustrate the effect of task and position on affected arm reach percentage. Regardless of pre-stroke dominance, a majority of patients performed most if not all reaches in ipsilateral space with the affected arm. However, at midline and in contralateral space distinct patterns in reaching preference emerged between the DA and the NDA patient groups. DA patients performed a greater number of tasks at a greater number of positions, with each patient performing between 3 and 5 different tasks at midline, and between 1 and 3 different tasks in contralateral space. In contrast, the NDA patients performed between 0 and 3 different tasks at midline and did not perform any contralateral reaches. These similarities within the DA or NDA groups were observed regardless of patients having mild or moderate impairment.

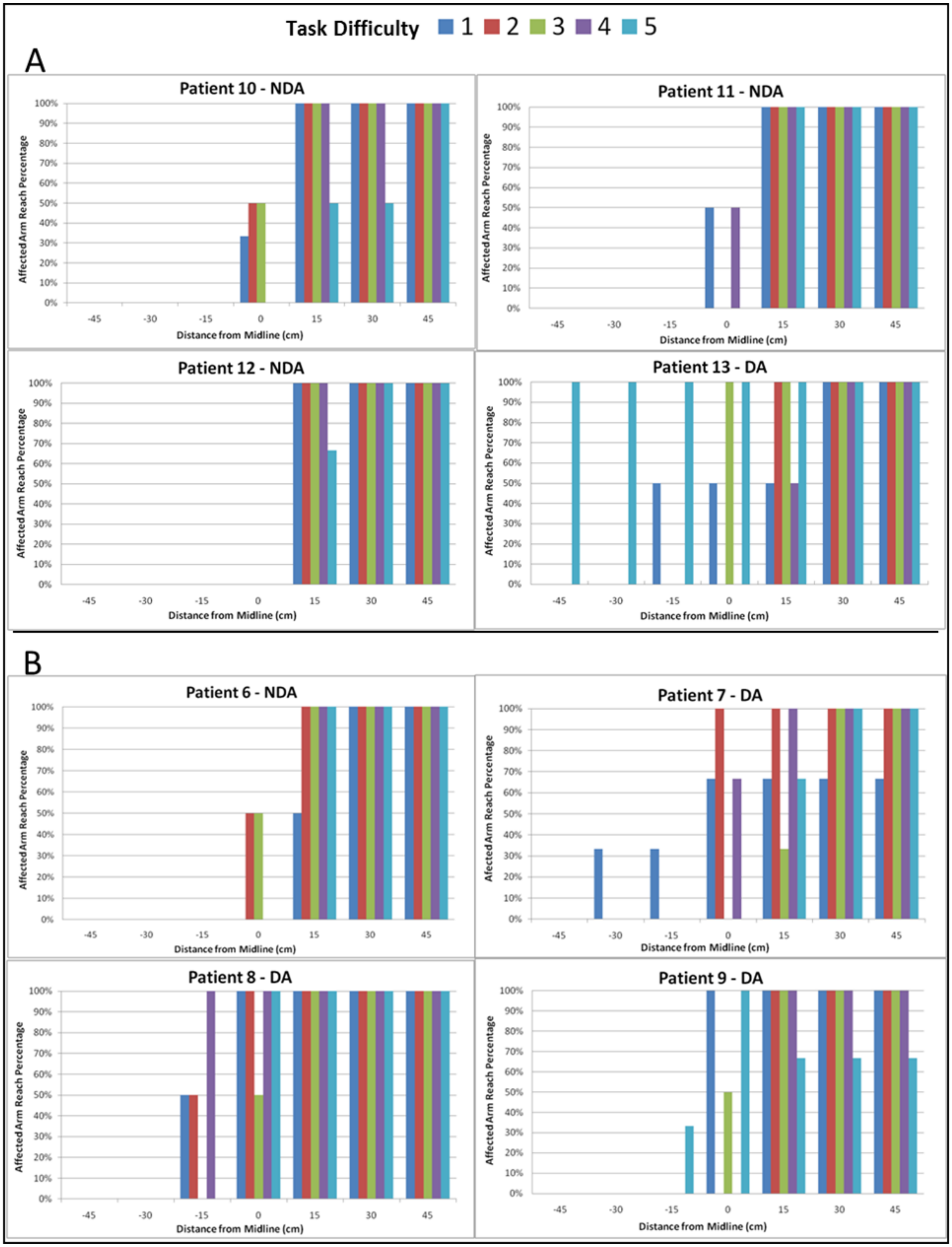


Figure 48: Comparison of reaching profiles for patients in the mild (A) and moderate impairment group (B). Bars indicate affected arm reach percentage for each task and location (further to the right is ipsilateral with respect to the affected arm). DA denotes patients with their dominant arm affected, and NDA denotes patients with their non-dominant arm affected.

8. Discussion and Conclusions

The overall goal of this thesis was to assess the feasibility of using a performance-based tool to assess degree of hand preference after stroke. This study highlights the development of a novel protocol to quantitatively assess upper limb preference which was successful in revealing person and task-specific difference in preference and movement characteristics. Overall the results of this work revealed that the design approach had the potential to reveal patient specific differences in upper limb preference that may be a potentially important tool in assessing upper limb recovery after stroke. However, the work also highlighted the complexities of the potential relationships between limb preference and both impairment and pre-morbid hand dominance.

Two studies were conducted to achieve our goal and overall we found that as impairment increased there was a decrease in affected arm reach percentage. However, this trend only approached statistical significance likely due in large part to the heterogeneity of the patient group. A modest trend was observed revealing that patients who had their dominant arm affected tended to rely more on the affected limb in spite of the impairment though this difference was not statistically significant when evaluated across the group. Finally, in contrast to the hypothesis there was no significant effect of task difficulty on overall reach percentage, although trends in the data suggest that task location and pre-stroke dominance may interact to influence task-specific hand preference.

For the initial protocol design in study one, there was evidence to support the effect of pre-stroke hand dominance as all but one patient who had their non-dominant arm affected performed all reaches with their unaffected arm. In addition, one patient with their dominant arm affected performed all reaches with the affected arm, leaving only three patients who performed reaches with both arms. This led to a redesign of the protocol and test in Study 2 to decrease the probability that all reaches would be performed with one arm, by varying the distance from each arm to the target (making reaches across the body a greater distance) and not just the workspace location. Observations from this new design were promising, as there were only two patients who did not perform any reaches with their affected limb despite an ability to do so, thus allowing our two main hypotheses to be tested against each individual patient's reach percentage.

8.1 Hypothesis 1: Affected arm reach percentage will decrease as impairment increases

While the hypothesis that overall affected arm reach percentage would decrease as impairment increased, was not supported there was the presence of a trend in the association. There was a great deal of variability within groups of patients having similar impairment and this likely contributed to a reduced ability to detect a statistically significant association. Some individual patients in the moderate impairment group even had a higher overall reach percentage than others in the mild impairment group. Although there were no patients with a 'normal' impairment score (CMSA 7), there were some patients with an overall reach percentage higher than the controls (when compared by arm dominance). Of eleven patients with the ability to complete tasks with their affected arm, nine chose to use their affected arm in the voluntary condition for tasks that matched their ability.

Although there was not a significant effect of impairment on affected arm reach percentage, results still indicate that impairment supersedes other factors. This was most evident when the affected limb was very severe as was the case in patients 1 and 2. These individuals did not have the capacity to perform specific movements with the paretic limb and therefore this profoundly influenced limb preference. In general, impairment dictates the capacity to complete each task and if the ability exists then other factors such as pre-stroke hand dominance appear to influence limb preference. However, when patients had the capacity to complete the tasks, regardless of the time it took, other factors such as task location, pre-stroke dominance and those discussed below, influenced preference. Therefore, although it is not sufficient to explain overall reach percentage, it remains important to examine the relationship to impairment before determining the relationship between pre-stroke hand dominance and post-stroke hand preference.

If there was a very strong correlation between impairment and overall reaching percentage then the test we have developed would be redundant, as impairment scores alone would be sufficient to predict preference. Hand preference after stroke is likely influenced by characteristics of impairment (side and severity) as well as non-impairment factors, especially pre-stroke hand dominance (side and degree). It is anticipated that post-stroke preference could provide better insight into understanding the link between impairment and actual amount of affected arm use in activities of daily living. This is based on studies indicating that task-specific preference in the healthy population is linked to the actual amount of use of one arm over the other in unimanual tasks (Annett, 1970; Bryden, 1977). There are several possible reasons that may have contributed to the lack of statistical difference between impairment and overall reach percentage. First, as commonly reported in the literature, impairment measures are only weakly correlated with function and function with actual amount of use (Andrews, 1979; Taub and Uswatte, 2003; Morris and Sterr, 2002). Second, the method we used to classify impairment (average CMSA score), may not have fully represented all upper-limb impairments. Finally, there were methodological limitations specific to this study that decreased statistical power, most likely the high degree of between subject variability and constraints limiting number of trials collected.

Correlation between impairment and preference

Our results are congruent with research indicating that level of impairment does not solely dictate function and function actual amount of use (Andrews, 1979; Taub and Uswatte, 2003; Morris and Sterr, 2002). This was observed in the comparison of two patients from the moderate impairment group. Patient 8 (CMSA arm 4, hand 5), had 0kg of force for grip and pinch strength, and still performed 61% of overall reaches, and all possible reaches in ipsilateral space with the affected arm. In this case the impairment of muscle weakness of the hand/wrist had little bearing on preference as maximum force was not required for the tasks in this study and is not required in most activities of daily living. On the other hand, Patient 5 (CMSA arm and hand 5), had the highest grip strength of any patients and the capability to complete all tasks, yet he did not perform any reaches with the affected arm, possibly due to the presence of upper-limb motor ataxia. It is therefore important to determine task-specific function as this may also influence preference.

However, providing patients had the same task-specific functional ability with the upper-limb there are still other factors influencing preference, such as time since stroke, amount of therapy, shoulder pain and pre-stroke dominance. The effect of pre-stroke dominance may partially explain the difference in preference within patients in the same impairment group, and will be discussed in the next section. Shoulder pain is of particular importance as patients may be able to complete the task, and even complete it at a speed comparable to their unaffected arm; however, pain may prevent them from preferring the use of their affected arm. This may have been the reason for Patient 4 not performing any voluntary reaches, as he was the only patient below CMSA 6 with a score of 4 for shoulder pain (1 is most severe pain, 7 indicates no pain). Qualitatively, the patient had indicated that the pain kept him from wanting to perform activities requiring shoulder flexion. Shoulder pain is common, affecting up to 72% of patients with hemiplegia (Bohannon et al., 1995; Roy et al., 1994; Van Ouwenaller et al., 1986), and is linked to poor recovery of arm function and ability to complete activities of daily living (Roy et al., 1994). As well, therapy might increase preference of the affected limb in the short-term as patients are being encouraged to use the affected limb. Time since stroke may also affect preference as patients may initially be motivated to use their affected arm, but after time if a plateau is reached this motivation may diminish. In future, it would be beneficial to examine these factors and others in order to clarify the relationship between impairment and preference.

Limitations of using CMSA to represent impairment

For this study, severity of upper-limb impairment was represented by the average of CMSA scores for the arm and hand. CMSA impairment inventory of the arm and hand is a valid and reliable measure used to classify patients into homogenous sub groups based on their stage of motor recovery (Gowland et al., 1993). Understandably, the CMSA scores for arm and hand cannot account for every possible impairment contributing to upper-limb dysfunction. Thus impairments such as strength, endurance, co-ordination and motor sequencing may not be fully evaluated, especially in the moderate impairment group.

Although a certain degree of muscular strength and endurance is necessary to complete tasks in the assessment, the CMSA does not explicitly evaluate either of these elements. As well, it is not until the higher levels (6,7) that patients are required to complete tasks in a time limit. This may affect the ability of the CMSA score to reflect motor planning and sequencing deficits as the patient may be able to complete the required tasks but would be slower to plan, initiate and execute the required movements. This was observed in patient 6, who may have had motor planning deficits and was much slower than all other patients in the moderate impairment group, but was still able to complete the tasks correctly. Co-ordination between the arm and hand is also not evaluated until higher levels, and only in the hand inventory; for all other levels the movements require only using the arm or hand separately. As patients with upper-limb ataxia have difficulty with co-ordination, they may have impairment scores in the moderate range but have very different task-specific ability. Therefore, using CMSA scores to represent impairment may have contributed to a lack of significance between impairment and preference.

Methodological limitations

There were also limitations in the study design that would have reduced statistical power and thus the ability to observe a significant effect of impairment on overall affected arm reach percentage. Due to temporal constraints of clinical testing and the desire to include several tasks and positions, there were only a few trial repetitions in the patient study. Ideally one may have preferred to have acquired 5 repetitions of each task at each position but this would have required a total of 175 trials. In contrast we obtained 2-3 repetitions of each task at each position. The low number of trials limited the ability to properly document important strategy changes such as patients switching hands after the first few trials at each task. Further, the exploratory nature of the study meant that we included any patients who were willing to participate, could follow a two-step command and had a minimum CMSA score of 2. This created a wide range of variability between patients in CMSA values (including shoulder pain and postural control), age, time since stroke, other motor dysfunctions (ataxia, motor programming deficits), cognitive deficits, sensory deficits and pre-stroke side and degree of hand dominance.

Using the average of the arm and hand CMSA scores may have also contributed to variability in function within impairment subgroups. Patients with a higher arm than hand score may have a very different impairment than patients with a higher hand score. Those with a lower arm than hand score would find the reaching component more difficult, and may perform fewer reaches at all task levels resulting in a lower overall reach percentage, despite the same overall average. As indicated in the previous sections, these factors could all influence function and preference to varying degrees for each patient. This of course made it difficult to conduct group comparisons due to the heterogeneity of the groups.

8.2 Hypothesis 1B: Patients with their dominant arm affected will have a higher reach percentage than those with their non-dominant affected

The results revealed a modest difference in affected arm preference when comparing the patients with their dominant versus non-dominant arm affected. As predicted this difference was characterized by a greater reliance on the affected arm when it was reported as dominant prior to the stroke. However this difference was not statistically significant. The difference between the two groups of patients was similar to the difference in the controls' dominant and non-dominant arm reach percentage; however, the control subjects did have a significantly higher overall reach percentage for the dominant arm. The lack of statistical difference in the patient group was likely associated with the degree of heterogeneity among the stroke patients compared to the controls.

Although there was not a significant difference in overall affected arm reach percentage between patients with their dominant or non-dominant arm affected, the differences revealed by workspace location may be more important. First, the significantly greater percentage of reaches at midline by those with the dominant limb affected is evidence that when the reach distance is equal and workspace location is neutral, the patients are much more likely to use their affected arm when it was their pre-stroke dominant limb. Combined with the fact that all dominant arm affected patients performed reaches into contralateral space, this could indicate that in natural conditions they may be more likely to reach across a wider range of spatial locations. This is crucial as the egocentric location of tasks to be performed is constantly changing as people move throughout their environments; constantly changing the probability of which arm will be chosen. This is reflected in the qualitative responses we received on the handedness questionnaires to weakly lateralized tasks (picking up objects, turning on switches, opening drawers): a common response was that it “depends which hand is closer.”

Further, the willingness of the dominant arm affected patients to reach to a wider range of locations reflects the importance of pre-stroke dominance on post-stroke preference. There is a possibility that this willingness may indicate an increased chance of using the affected arm to assist the unaffected arm in tasks that have the option of being bilateral. A study by Rinehart et al. (2009), did not find a difference between unimanual use of the affected arms in activities of daily living in patients with either their dominant or non-dominant arm affected. However, they did find that patients with their dominant arm affected used their affected arm in bimanual tasks significantly more than those with their non-dominant arm affected. One major difference between the current study and that of Rinehart et al., is that they did not manipulate the location of the tasks. Our results also did not find an overall difference in reach percentage, rather the differences emerged when the midline and contralateral spaces were examined separately. This reinforces the idea that it is important to vary the workspace location of tasks, as well as including tasks with the option of being bimanual, to allow assessment of the full continuum of hand preference.

Methodological limitations

Methodological reasons for not detecting a statistical difference between those with dominant versus non-dominant arm affected are similar to points discussed before, such as a low number of trial repetitions, time constraints and heterogeneity. The heterogeneity is further increased in this study since, unlike most stroke studies, we did not exclude left-handed participants and consequently had some potentially important patient differences. For example, we included one patient who was left-handed and two patients who were right-handed before the stroke but were forced to switch from being left-handed in childhood. In handedness literature, left-handed individuals are commonly less lateralized than right-handed individuals (Gabbard, Iteya and Rabb, 1997), and are more comfortable with reaching into contralateral space to perform tasks as our world is designed for the majority right-handed population (Porac and Coren, 1981). This may have resulted in a hand preference after stroke that was unique from patients who were right-hand dominant pre-stroke. Although most patients were right handed, all patients represent a continuum rather than a dichotomy of pre-stroke hand dominance as is reported by other studies (Annett, 1970; Bishop, 1998). Such individual differences also contribute to variability in post-stroke hand preference. Therefore, as in the healthy population, it is important to consider not only the direction of pre-stroke hand dominance but the degree as well.

Another factor contributing to a non-significant difference between patients with the dominant and non-dominant limb affected may have been the adapted study design in study 2. In the first study all positions were equidistant and the dominant affected patients reached to all areas of workspace much more frequently than the non-dominant patients in study one, and also more than the dominant affected patients in study two. This resulted in a higher overall affected arm reach percentage for the dominant affected patients and a greater gap in the overall percentage between patients with their dominant or non-dominant arm affected. In the new design, the distance to task locations is actually further in contralateral space, and only equidistant at midline. One initial concern with the new design was that preference would be dictated entirely by proximity - that the hand closest to the task location would reach 100% of the time and the midline would be the only location to observe an effect of preference. It appeared, based on the increase in affected arm reaches in non-dominant affected patients compared to study 1, that proximity did play some role, as the increase was only observed in ipsilateral space. These findings indicate that the non-dominant affected patients may be more likely to use the affected limb when the object is in close proximity. In the first study, the non-dominant affected patients were more likely to use their unaffected (dominant) arm to perform all tasks since the distance to the targets was equal regardless of the hand they chose. Whereas, in study 1, the dominant affected patients (similar to healthy controls), performed a majority of reaches in ipsilateral space and at midline, and also reached into contralateral space. In study 2, dominant affected patients still had this reaching pattern, albeit with fewer contralateral reaches, indicating that they are willing to reach a further distance and are not only influenced by proximity. Therefore, despite a smaller difference in overall reach percentage between the patients with their dominant or non-dominant arm affected, the fact that dominant affected patients were actually willing to reach a further distance lends to the idea that pre-stroke dominance has important influence, above and beyond simple reach distance, on post-stroke limb preferences.

8.3 Hypothesis 2: Affected arm reach percentage will decrease as task difficulty increases

Overall our results did not support this hypothesis, as there was no statically significant effect of task difficulty on reach percentage for the patients or control subjects. However, the hypothesis may have been partially supported by the qualitative observation of a weak negative relationship between increasing task difficulty and overall reach percentage among those patients with the non-dominant arm affected. In contrast, there was a weak positive relationship observed qualitatively between task difficulty and affected arm use in the dominant affected group, which was congruent with the weak positive relationship observed qualitatively in dominant arm use in controls. Further breakdown by workspace location revealed that the dominant affected group increased preference in the midline and contralateral reaches for the more difficult task conditions compared to the non-dominant arm affected group. Collectively these observations lend some support to the idea that task challenge may determine limb preference specifically in relationship to the use of the pre-stroke dominant arm. The apparent increase in reaches for the dominant affected patients and control subjects is in agreement with the handedness literature that indicates increased dominant arm use as skill requirements are increased (Calvert and Bishop, 1998). In a healthy population, the dominant arm is more likely to reach farther into contralateral space as skill requirements increase. This is potentially important since task challenge, naturally varying in everyday life, is less commonly addressed during clinical assessment of arm preference and use after stroke.

Task-specific differences in DA and NDA patients

Of the patients who were able to complete all tasks, 8/10 performed between 40 and 60% of reaches with their affected arm. Of these patients, the preference to use one hand over the other at each location was influenced by their pre-stroke dominance and not by their impairment group, or task-specific function (reflected by the time taken to complete each task). This meant that there was no difference in task-specific preference or overall affected arm reach percentage between those who performed significantly slower with their affected arm and those who did not (with the exception of the most severely impaired patient who had a much lower reach percentage than all other patients). Even patients who performed tasks significantly slower with the affected compared to the unaffected arm, still chose the affected arm just as often as those who had equal movement times between arms. Therefore, previous hand dominance may be influencing the motivation to use the previously dominant arm despite the challenges in control as reflected by movement times when using the affected arm.

Methodological limitations

Using a fixed order of tasks rather than random, may have led to practice effects, such that as task difficulty increased the patients would have had more practice and the increase in difficulty would have been different than if the trials were randomized. However, the rationale behind having a fixed order of tasks was to minimize the confusion and amount of time that may resulted from constantly switching between 5 tasks. As well, the purpose of going from the easiest to hardest tasks was to minimize any frustration that would be generated by asking a patient to perform the fine control task (task 5) if they were not even capable of a fixed grasp (task 3). With the current set-up the test would be stopped when the patient could no longer perform the task with their affected arm.

The manipulation of task difficulty was based on increasing the distal requirements, while proximal requirements stayed relatively constant. However, in this study almost half of the patients were less impaired in their hand than their arm, which is contrary to the literature that supports a proximal to distal recovery profile (Brunnstrom, 1966; Twitchell, 1955). The patient's ability to reach (which was necessary for all tasks), would have had a greater impact on their overall affected arm reach percentage rather than their ability to complete the distal components of the task. This may have contributed to 6 of 13 patients having no increase in movement time across the first four tasks. This may have further diminished the effect of task difficulty on reach percentage if almost half the patients could perform the first four tasks in the same amount of time.

The relatively low degree of skill required to complete tasks may have also contributed to the lack of effect of task difficulty on affected arm reach percentage. In choosing the tasks for this study the degree of motor control was manipulated, rather than the skill requirements. It was expected in designing the study that the skill demands were sufficiently difficult to elicit the lateralized performances seen in the control population when skill demands are altered, but our results indicate that the task gradations were not sufficient to elicit differences in limb preference in the eight patients who performed reaches voluntarily, with the exception of task 5 (fine control task). As well, tool use was excluded from this preliminary study in order to solely evaluate motor control and not tool use which could be affected by apraxia, and other cognitive impairments.

In the healthy population a strong preference is observed for skilled tasks and a weak lateralization for unskilled tasks. A skilled task is defined as one that requires spatial precision (small target) and a complex sequence and co-ordination of movements (i.e. manipulating a tool) (Steenhuis and Bryden, 1989). Our first four tasks required an increasing amount of distal control, but were all unskilled tasks. The most difficult task (picking up and placing a dime) did require a high degree of fine motor control and spatial precision, and created the greatest degree of lateralization of all the tasks. However, the sequence of movements could be performed in any manner that accomplished the task and without time limits. In future, to elicit further lateralization, especially in patients with mild impairment, the inclusion of skilled tasks, especially tool use, would be necessary. Further, bimanual tasks could be included to observe which hand takes the dominant (manipulative) role and which takes the non-dominant (supportive) role, or even if the patient attempts the entire task with only one hand. To avoid the complications of including tools, the task conditions could also be altered by increasing the need for accuracy and movement speed. For example, accuracy could be increased by requiring patients to contact and grasp the same cylinder, but with an object balanced on top that would fall if contacted, grasped or released with excessive force. This would further challenge upper-limb control and may change patients' ability to complete the task successfully or increase the time taken to complete the task. Both of these outcomes could potentially decrease preference for affected limb use. Time limits could also be imposed such that tasks had to be completed before a timer ran out. Movements such as reaching commonly show increased movement time after stroke as a result of muscle weakness, impairments in motor planning and sequencing, and loss of interjoint co-ordination (Parker, Wade and Langton, 1986). Forcing patients to complete tasks more quickly would challenge patients who could complete the tasks with their affected arm, but may not have the capacity or preference to use their affected arm when speed is required. This would allow the inclusion of the same tasks in the current study, but would likely illicit greater lateralization, and greater differentiation between the mild and moderate impairment groups. Increasing the type of tasks included would also improve the generalizability of the test for real-world use.

8.4 Potential to use limb preference and kinematics to measure within patient recovery

The ultimate goal of this research was to determine preference as a means of better understanding the link between impairment and actual amount of affected arm use in activities of daily living. This is based on studies indicating that task-specific preference in the healthy population is linked to the actual amount of use of one arm over the other in unimanual tasks (Annett, 1970; Bryden, 1977). As indicated previously, impairment measures are not sufficient to explain function, and function is only weakly correlated with actual amount of affected arm use. Therefore, using this measure in conjunction with clinical measures of impairment may allow better sensitivity to detect within patient changes throughout recovery. The tool could also identify patients who may not be using the affected limb as much as they can, (i.e. preference does not match ability), and may benefit from therapies that encourage affected arm use such as constraint-induced movement therapy.

The tool could also be combined with more advanced kinematic analysis, which would enable simultaneous evaluation of patients' movement kinematics as they perform tasks that are function based (involve reaching to an object), but specifically target impairment stages due to the gradations altering proximal to distal requirements. While such detailed kinematics are unlikely to be used in a routine clinical setting they could provide clinical researchers with parameters such as movement time, peak velocity, timing of movement components, variability in kinematic measurements and interjoint co-ordination. These parameters are often disrupted following stroke (Archambault et al., 1999; Cirstea, 2000; Levin, 1996; Parker, Wade and Langton, 1986), and their analysis could inform researchers on specific impairments and enable them to monitor natural recovery and response to treatment interventions. Important to this study, changes in kinematic parameters could be correlated with changes in arm preference.

8.5 Limitations

General limitations that decreased statistical power for all hypotheses stem from the exploratory nature of the study and the inherent variability of a patient population. As this evaluation was conducted in concert with a standard battery of tests and not on its' own, there were strict temporal constraints to prevent patient fatigue. These constraints greatly reduced the desired number of repetitions for each task at each position.

Also due to these necessary temporal constraints, the amount of equipment, and resulting set-up time, was kept to a minimum. Therefore, the only measurements we obtained for trunk motion was the peak acceleration from the accelerometer placed on the back. This proved to be a less than desirable representation of trunk compensation. The values for trunk compensation were not reflective of those observed qualitatively from the video evidence, and only showed an effect of arm used for reaching in four patients. The peak acceleration may have been influenced by each patient's speed, and with the more impaired patients moving the slowest their peak trunk may also have been low and therefore we would not have been able to conclude that there was much trunk compensation. In patients with similar movement speed between hands the acceleration may have better meaning; however, this only occurred in the least impaired patients. The best representation would be to measure maximum trunk displacement as a function of the total reach, and could be obtained using motion capture systems such as Optotrak.

Another limitation may have been associated with the environment in which the test was conducted. A majority of the patients were still receiving their physiotherapy in the area where we conducted the testing. For convenience many patients had their rehabilitation sessions prior to testing, and all patients had their affected arm function tested prior to this test, which may have cued them to use their affected limb. As well, the presence of physiotherapists in the room helping with the testing session may have provided further incentive to some patients to use their affected arms, as these are the same physiotherapists promoting affected arm use in their therapy sessions.

8.6 Future Directions

Future studies would allow the ability to investigate why patients chose one arm over the other when given the choice. Some obvious reasons exist in certain situations, including the task location (distance and workspace location) and the ability to complete the task. However, other reasons may exist such as influence of pre-stroke hand dominance, perceived effort/difficulty, perceived ability, pain, other motivation (presence of physiotherapist, effects of being in a testing environment and having performance recorded). Possible methods to examine these factors could be having matched questionnaires with perceived ability/difficulty with the exact tasks that are to be performed in the preferential reaching task. As well, having a large number of subjects with similar characteristics (hand affected, impairment etc.) and testing specifically for effect of degree and type (i.e. which tasks they performed with either hand pre-stroke) of pre-stroke dominance. Identifying factors underlying amount of use and especially learned non-use would allow therapists to specifically direct their efforts at the underlying cause.

Although an important future step would be to include tasks with a greater level of skill level, it would be equally valuable to include tasks with less proximal control required. In this study we manipulated the distal requirements, to target the stages of stroke recovery; however, in this small sample, a majority of the patients had a lower impairment score for their hand and not arm, contrary to the profile usually postulated in stroke recovery literature. As well, shoulder pain precluded at least one patient from reaching. Therefore, including tasks that vary distal demands without requiring a full reach would provide the opportunity to observe task-dependent hand preference in these patients.

As the first study seemed to be more sensitive to the differences between dominant affected and non-dominant affected patients, but was not sufficient to find a degree of preference in the non-dominant affected patients, a hybrid between these two designs may be optimal. The tasks would be randomly distributed throughout all areas of workspace, allowing examination of near and far positions in all areas of hemispace, as well as those that are equal and unequal distances from both arms (all distances within 90% of both arms' max reach). This set-up would provide optimal insight into post-stroke hand preference in all areas of reachable workspace.

Future studies combining the modifications described above with detailed kinematic measures would enable simultaneous evaluation of their quality of performance (impairment), in addition to the tasks they can complete (function) as well as willingness to spontaneously use their affected arm. Methods to improve collection of kinematic measures, without adding significant time to the testing protocol as well as requiring too much equipment to be attached to the patient would have to be considered. Possible options would include high resolution video recording, or Optotrak, which would allow measurement of peak velocity, movement smoothness, peak hand aperture, movement time and trunk displacement.

Another future direction would be to investigate more fully the propensity of some patients to switch from one hand to the other at some point during task performance. This may provide insight into a patient wanting to use their affected limb and then not being able to. In contrast, other patients may first attempt reaches with their unaffected arm before realizing that the affected limb is capable and much closer to the target. We only have qualitative descriptions of these 'switches' and there appeared to be no reliable trend, with approximately half the switches occurring from the affected to unaffected and vice-versa. One patient, as obvious from the previous visit (where all reaches were made with the affected arm), was attempting to use the affected arm as much as possible, until realizing that the other arm would be much closer and faster to use, and thus switched to the unaffected arm. Other patients had been using the unaffected arm in these far contralateral reaches, and then realized that they were in fact capable of completing that task with the affected arm and also switched mid-reach. Without more detailed kinematic measures, it is not possible to conclude exactly when these switches took place, or why (they may have switched arms because one could complete the task more quickly or regardless of speed, one arm may have been more comfortable). Future studies would allow these more detailed kinematic analyses, as well as including a follow-up period to interview the patients to more fully understand this behaviour.

8.7 Conclusions

This study has demonstrated the feasibility of implementing a performance-based assessment of hand preference into a standard clinical protocol. In addition, the work highlighted that if impairment does not preclude the ability to complete a task, pre-stroke hand dominance will have a distinct influence on post-stroke hand preference. This may not be manifested in an overall higher reaching percentage with the affected arm, and may elicit itself differently for each individual patient depending on task difficulty and task location. However, in general patients with their dominant arm affected are more likely than those with their non-dominant arm affected to perform a greater number of tasks across a greater area of workspace. This may be indicative of a greater amount of use in everyday life; however, this relationship requires further research.

The results of this study indicate that it is feasible to use a performance-based preferential reaching task to elicit task-specific differences in stroke patients. The entire protocol was accomplished within 10 minutes, with minimal equipment attached to patients, allowing the possibility of integrating this tool into a typical test battery. Therefore, with validation and modifications indicated, this tool could be used as an objective measure to provide additional insight into the factors underlying amount of affected arm use following stroke.

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