Abstract

Stroke is a condition that arises from partial or complete blockage of blood flow to parts of the brain. Upper limb impairments (sensorimotor deficits) usually occur as a result of stroke. Assessment and diagnosis of the resulting upper limb impairments is important for effective rehabilitation and proper recovery. In terms of assessment, current ordinal scale systems used are inherently subjective and incorporate coarse rating scores (Chedoke McMaster, Fugel Meyer test, etc.). These scores do not provide clinicians with information regarding the underlying impairments which is important for effective rehabilitation therapy.

We investigated the use of a reaching task on a bi-lateral upper limb robotic device (KINARM), developed by one of our team members (Stephen Scott), to assess upper limb impairments due to stroke. Control and stroke subjects were instructed to reach with both arms on the robotic device to illuminating spatial targets as quickly and as accurately as possible. We first developed a tool that would aid in locating targets where reaching impairments are visible for stroke subjects. From the Kinematic data collected, we then selected reaction time and first peak velocity of the hand and investigated their potential for separating control and stroke subjects. Results of our analysis showed the potential of both parameters as good quantitative assessment measures. In particular results for reaction time presented symmetrical differences
between both arms were of main interest in this thesis. Such differences presented the potential of sensitivity in showing subtle impairments.
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Chapter 1

Introduction

Stroke is the second leading cause of death worldwide. Survivors of stroke often suffer severe impairments usually involving control and use of their upper limb(s) [28]. This thesis explores the use of a robotic device called KINARM for assessing upper limb impairment to assist clinicians in assessment and rehabilitation.

1.1 Motivation

Stroke occurs due to disturbances in blood flow to the brain. The body parts and functions that are controlled by the area of the brain starved from blood are usually compromised. Upper limb impairments and possibly complete paralysis are a common result of brain stroke [22].

Currently, most clinical assessment of impairments of the upper limbs includes physical assessment and visual observation by rehabilitation therapists. The resulting clinical scores are inherently subjective and offer little information about details of underlying impairments [16]. Assessment of upper limb impairments is therefore crucial
as it greatly assists in rehabilitation therapy planning. Hence, more objective and accurate methods of assessment would improve on both diagnosis and rehabilitation.

Although robots have been extensively used in rehabilitation, little work has been done in their use as an assessment tool [9, 40]. KINARM (Kinesiological Instrument for Normal and Altered Reaching Movements) is a robotic device that was developed by Dr. Stephen Scott of the Department of Anatomy and Cell Biology at Queen’s University. The device was initially developed to study the activity of neurons during various behavioral tasks in non-human primates [2]. More recently, a human-sized KINARM was developed to study fundamental issues in motor control and learning in the upper limbs of humans [3].

Different tasks on the KINARM robot have been developed to investigate possible sensorimotor impairments that could be caused by stroke [9]. A task selected for investigation in this thesis involves subjects reaching with the robotic arm to different virtual targets. Stroke and control subjects admitted to our study were required to complete reaching movements to virtual targets with their upper limbs positioned on the robotic device. Data recorded by the robot from the hand, elbow and shoulder are vast and include parameters such as hand velocity and subject response time.

1.2 Hypothesis and Goals

It is hypothesized that the reaching task developed would capture some subtle impairment in upper limb reaching caused by stroke and show differences between control and stroke subjects not visible to the naked eye. These differences might be notable when directly observing reaching patterns or indirectly analyzing parameters
calculated for reaching (response time, velocity etc). We then believe that further investigation of these differences could be used to develop objective scores that are useful in a clinical setting for rehabilitation use.

To date, simple visual diagrams of reaching were developed to assess reaching performance [9]. As well, there have been no attempts to formulate an assessment scheme using any of the parameters recorded by the robotic device. To investigate our hypothesis the following goals were identified:

a) Parameter Selection

Although the KINARM system provides a way of calculating parameters associated with reaching such as torques, velocities and angles, only selected two parameters for detailed investigation: subject response time (reaction time) and initial hand velocity (first peak velocity) were both analyzed. Our motivation in selecting these parameters was to study in depth two initial aspects of the reaching (response and initial velocity) and identify their potential at capturing any impairments due to stroke..

b) Traditional Analysis

First we use similar methods of analysis that have been previously used to investigate differences between control and stroke subjects [9]. Our goal was to identify possible weakness in these methods and therefore motivate the need for new methods of analysis. In the following, we summarize the two main traditional methods of analysis that were used in our research.
i) **Traditional reaching diagram:**

Simple visual diagrams investigated earlier [9] allow the user to visualize hand movement patterns for each reaching attempt. In our research we used these simple visual diagrams to study reaching behavior for control and stroke subjects.

ii) **Linear parameter analysis:**

Previous work on parameter analysis from the KINARM device included simple linear analysis across all target directions for each arm. The goal was simply to assess the parameter’s potential at separating control and stroke subjects [9]. In our thesis we use similar analysis to investigate the potential of *reaction time* and *first peak velocity* at separating control and stroke subjects.

c) **New Analysis**

In the following we present a summary of new methods of investigation that include a new visual tool for diagnosis and a new framework for data analysis

i) **New reaching diagram:**

The traditional reaching focuses on allowing the researcher to directly visualize all reaching attempts to all movement directions for a given subject. As a result of many reaching attempts and movement directions being visualized, it is sometimes hard for the naked eye to determine movement directions where the impairment in reaching to the target is most visible. We therefore set out to research and develop a different visual tool. We were interested in a new visual tool that could be quicker and easier at identifying impairments to specific movement directions.
ii) **Establishment of a Framework for parameter analysis:**

Linear parameter analysis across all movement directions for a given arm presents a challenge in understanding the underlying impairments in reaching. Observing separation of control and stroke subjects for some targets over others [9] does not offer a direct explanation of the underlying impairment in reaching.

Difficulty in reaching towards a specific target (movement direction) could be caused by one of two impairments. The first impairment relates to the inability of a subject to see, sense or respond to virtual targets in certain movement directions. This could be due to minor visual deficits or spatial neglect [40]. The second impairment relates to problems in moving to certain directions due to specific muscular impairments resulting in poor reaching performance [6,18,19].

A framework of data analysis was developed based on our understanding of both impairments. For each parameter selected (*reaction time* and *first peak velocity*), we expect that one of these two impairments would be the dominant contributor to any abnormal (different from control subjects) parameter value for a given stroke subject.

iii) **Correlation with clinical scores:**

An essential step following research on a framework for parameter analysis was to identify the usefulness of such framework. We therefore selected two clinical scores currently being used to assess upper limb impairments of stroke subjects and correlated them with our summarized parameter values. It is expected however that
the clinical scores selected are able to capture impairments that are not detected by our KINARM device and vice versa.

**iv) Developing a new Clinical Score:**

After research on developing a new visual diagnostic tool and selecting the appropriate framework for analyzing each of our selected parameters, we were interested in the development of a scoring system that could be used in a clinical setting. Our research was thus focused on identifying parameter differences between control and stroke subjects that could be properly used in scoring normal reaching behavior (control) and impaired reaching behavior (stroke).

**1.3 Thesis Organization**

Chapters 2 details the condition of stroke and its effect on upper limbs. Chapter 3 presents robotic technologies that have been used for rehabilitation and assessment of upper limb impairments due to stroke. Chapter 4 details methods for achieving thesis goals (See Section 1.2). Chapters 5 and 6 discuss results using traditional methods of analysis and new methods of analysis respectively. Chapter 7 presents in details a new clinical scheme for assessment of reaction time. Chapter 8 offers conclusions and suggestions for future work.
This chapter discusses in detail the condition of stroke and its effect on upper limb function as upper limb assessment is the focus of this thesis. The need for accurate techniques to assess impairments for rehabilitation therapy planning is discussed. As well, a review of some current clinical tools used for assessment of upper limbs of stroke patients is presented.

2.1 Stroke

Worldwide, stroke is the second leading cause of death, responsible for approximately 4.4 million (9 percent) of the total 50.5 million deaths each year. Over 300,000 Canadians are currently living with the effects of stroke, which costs the Canadian Health Care System approximately $2.7 billion annually [28].

The human brain is a complicated organ that consists of billions of neurons that allow for sensory, motor and intelligent processes such as thought, sensation, speech and
limb movements. Since neurogenesis (neuron creation) is very limited in the adult brain, it is important that those neurons receive sufficient vital nutrients and oxygen through the blood vessels of the brain [16]. When stroke occurs, there is a decrease in supply of such vital elements to the neural tissues resulting in brain damage.

2.1.1 Types of stroke and resulting impairments

There are two types of stroke: a) ischemic stroke and b) hemorrhagic stroke. Ischemic stroke occurs when a blood clot forms in one of the blood vessels in the brain (blockade of blood flow). Hemorrhagic stroke occurs when a blood vessel in the brain ruptures and leads to bleeding. In both cases there is a disturbance in blood flow to different parts of the brain. This shortage in blood supply can result in destruction of neural tissue, due to oxygen and nutrient deprivation. Depending on the damage, paresis (paralysis) or hemiparesis, loss of sensation, loss of vision, loss of memory and the inability to speak or understand speech could occur [16]. In hemiparesis, deficits in the coordinated use of a limb are most evident in the limb that is contra-lateral (opposite) to the side of damage in the brain [15].

Spatial neglect is also a common impairment resulting from stroke. Uni-lateral spatial neglect is a condition which impairs a person's ability to look, listen or make movements in one half of their environment. This could therefore affect their ability to carry out essential tasks such as eating or reading [37].

Several aspects of stroke, including lesion size, location and age of the patient at occurrence, can be used to predict the extent of the post-stroke paresis as well as the prognosis of recovery. For example a lesion in the area of the middle cerebral artery
the brain affects the upper limbs more than the lower limbs whereas a lesion in the anterior (front) cerebral artery mostly affects the leg and foot. For this reason, there has been an interest by clinician for separate stages of assessment for the arm, hand, leg and foot. [8]

### 2.1.2 Effect of Stroke on Upper Limbs

One of the most common causes of stroke is occlusion of the middle cerebral artery, which supplies areas of the brain responsible for motor control of the upper limb. In the majority of stroke patients, the upper limb is more affected than the lower limb [22]. In the following we discuss the direct effect of stroke on upper limb function as well as the effect on theoretical aspects of reaching with the upper limbs.

#### a) Direct Effect on Upper Limb Function

Presentation of sensorimotor deficits in the upper limb includes muscle weakness [18], abnormal muscle tone [21], spasticity [21] and abnormal movement synergies [19]. The recovery of upper limb function is characterized by the emergence of stereotypic multijoint movement patterns that reflect a loss of independent joint control [6]. Initially muscles of the affected limb are weak; within days to weeks, flaccid muscles become hyperreflexive and spasticity is observed. Hyperreflexia or spasticity is defined as exaggerated velocity-dependent stretch reflexes in specific muscle groups. For example, volitional movements at the elbow brought about by biceps contraction could be affected due to stretch reflexes. Spasticity renders patients less able to increase movement speed.
Functional recovery of proximal muscles (closer to shoulder joint) tends to return before distal muscles (further from shoulder joint), and as it returns, the extent of the spasticity may decrease [6]. Although, some stroke patients do not recover any motor function in the affected limb(s), some research has suggested that training on reaching movements leads to improvement of upper limb performance in hemiparetic patients [29, 30, 41]

b) Other impairments in reaching:

Some studies have investigated other deficits in upper limb reaching due to a unilateral brain lesion [15, 33, 36]. These deficits were proposed as being relative to movement planning and execution in the brain rather than a direct result of muscle impairments. The unaffected arm (ipsi-lateral to brain lesion) was therefore investigated in these studies. The research focused on the task of reaching to virtual targets and parameters that were analyzed included reaction time, total movement time and the corrective component (number of corrective movements to reach the target). It was suggested that such aspects of reaching are affected by lesions resulting from stroke in specific areas of the brain [15, 33, 36].

2.1.3 Impact of stroke

Stroke is remarkable not for the damage that it inflicts but for the recovery that is possible. All stroke survivors recover to some degree. The best results are obtained when the patients are carefully selected for the appropriate type of rehabilitation, goals are determined and responses to rehabilitation are assessed [16]. With the increase in
research in stroke rehabilitation there has been an increase in demand for more accurate assessment measures for limb impairments of stroke patients.

### 2.2 Clinical Assessment of Upper Limb Impairments

Some of the tests used in clinical assessment of motor recovery are Chedoke-McMaster [1], Purdue Pegboard [4] and Fugl-Meyer [5]. The Fugl-Meyer scale was developed as the first quantitative evaluative instrument for measuring sensorimotor stroke recovery, on the basis of the findings of Twitchell and Brunnstrom’s concept of sequential stages of motor return in the hemiplegic (one sided brain lesion) stroke patient. Twitchell [6] noted in 1951 that motor recovery from stroke follows predictable, continuous and overlapping steps. No steps are skipped and the order in which the patient progresses is always the same. Brunnstrom [7] then classified the process of recovery into six definable stages for the upper and lower extremities. These stages were then used as baseline for the widely used assessment tools that have since been developed.

The Fugl-Meyer is a well-designed, feasible and efficient clinical examination method that has been tested widely in the stroke population [5]. Many studies aimed at understanding the sensorimotor deficits caused by stroke and concepts in recovery have used the Fugl-Meyer test as the primary clinical assessment tool [19, 22, 26]. Other studies that explore the use of robotic devices to improve rehabilitation have also used the Fugl-Meyer test to assess improvements in patients after robotic assisted rehabilitation [24, 25].

The Chedoke-McMaster method was developed on the same basis of the Fugl-Meyer test. Chedoke-McMaster was used mainly in our research work as it was
developed in McMaster University and is practiced more often by Canadian physicians [8]. It is also currently being used by clinicians at St. Mary's of the Lake Hospital Site in Kingston, Ontario.

The Purdue Pegboard test is a simple board test aimed at objectively assessing finger and hand dexterity. It has been shown that the Purdue Pegboard test can correctly predict the presence and laterality of cerebral lesions with 90% accuracy [27]. The Purdue Pegboard test is also currently being used by clinicians at St. Mary's of the Lake Hospital Site.

2.2.1 Chedoke-McMaster Inventory

The Chedoke-McMaster Inventory [1] consists of an Impairment Inventory and an Activity Inventory. The Impairment Inventory focuses on assessment of the stage of recovery of the shoulder, postural (positional) control, the arm, the hand, the leg and the foot. The Activity Inventory deals with scoring the Gross Motor Function Index and Walking Index.

In the Impairment Inventory, the clinician starts by assessing shoulder pain in order to assess the stage of recovery of the shoulder. First the patient assumes a sitting position on the side of a bed with his/her feet on the floor while the clinician carefully observes and assesses the position of the shoulder. The clinician then physically extends and adducts the patient’s shoulder and notes whether there is less than 90 degrees of pain free range. The clinician then looks at the description of each of the 7 defined stages of recovery and matches the description with his/her impression of the patient’s pain.
**Stages of the shoulder:** (Quoted from the Chedoke-McMaster Stroke Assessment: Development, Validation and Administration Manual, Section 7, Page 3 [1]).

“**STAGE 1:** Constant, severe arm and shoulder pain in more than just the shoulder.”

“**STAGE 2:** Intermittent, severe arm and shoulder pain in more than just the shoulder.”

“**STAGE 3:** Constant shoulder pain in just the shoulder.”

“**STAGE 4:** Intermittent shoulder pain in just the shoulder.”

“**STAGE 5:** Shoulder pain is noted during testing, but the functional activities that the client normally performs are not affected by the pain.”

“**STAGE 6:** No shoulder pain, but at least one prognostic indicator is present.”

“**STAGE 7:** Shoulder pain and prognostic indicators are absent”

To stage the arm, hand, leg and foot the clinician performs similar physical and observational experiments involving different tasks to assess for the different stages of recovery. For example, one of the tasks required in the third stage of the arm involves the clinician asking the patient to touch their chin and observes for sufficient elbow flexion for any part of the hand to touch the chin. Another task in the second stage of the hand involves the clinician extending and flexing the wrist 5 times with sufficient speed of passive movement to elicit and observe a stretch reflex. The clinician then matches his/her observations to the different stages of motor recovery for the affected limb (See below).
Stages of Motor Recovery for a paretic limb: (Quoted from the Chedoke-McMaster Stroke Assessment: Development, Validation and Administration Manual, Section 7, Page 6, Table 7.1 [1]).

“STAGE 1: Flaccid paralysis is present. Phasic stretch reflexes are absent or hypoactive. Active movement cannot be elicited reflexly with a stimulus, or volitionally.”

“STAGE 2: Spasticity is present and is felt as a resistance to passive movement. No voluntary movement is present but a facitatory stimulus will elicit the limb synergies reflexly. These limb synergies consist of stereotypical flexor and extensor movements.”

“STAGE 3: Spasticity is marked. The synergistic movements can be elicited voluntarily, but are obligatory. In most cases, the flexion synergy dominates the arm, the extension synergy the leg. There are strong and weak components within each synergy.”

“STAGE 4: Spasticity decreases. Synergy patterns can be reversed if movement takes place in the weaker synergy first. Movements combining antagonistic synergies can be performed when the prime movers are the strong components of the synergy.”

“STAGE 5: Spasticity wanes, but is evident with rapid movement and at the extremes of range. Synergy patterns can be reversed even if the movement takes place in the strongest synergy fast. Movements utilizing the weak components of both synergies acting as prime movers can be performed. Most movements become environmentally specific.”

“STAGE 6: Coordination and patterns of movement are near normal. Spasticity as demonstrated by resistance to passive movement is no longer present. A large variety of environmentally specific patterns of movement are now possible. Abnormal patterns of movement with faulty timing emerge when rapid or complex actions are requested.”

“STAGE 7: Normal. A "normal" variety of rapid, age appropriate complex movement patterns are possible with normal timing, co-ordination, strength and endurance. There is no evidence of functional impairment compared to the normal side. There is a "normal" sensory-perceptual-motor system.”

For postural control the clinician performs three different tasks to test for different stages of recovery. For example, to assess for the second stage of postural control the
clinician performs the following tasks: facilitated log roll to side lying, resistance to trunk rotation and static righting with facilitation. In the facilitated log roll, the clinician asks the patient to roll onto their strong side and observes how the patient performs. In the resistance to trunk rotation the clinician places one hand on the shoulder and the other over the hip, by quickly and passively moving the shoulder and hip in opposite directions the clinician carefully senses for a stretch reflex. The patient has to pass a certain number of tasks (two in the case of the postural control) in each stage to be classified as belonging to that stage of recovery. It is also important to note that for each stage of recovery there are different tasks designed to test for that stage. For example to test for the fifth stage of postural control the tasks involved are completely different from the ones for the second stage.

Finally, the Activity Inventory was designed to assess the patient’s functional level and not the precise ways in which the tasks are achieved. Therefore, while testing the focus is on task accomplishment and not the quality of movement. Finally, the Walking Index involves a number of tasks to be performed by the patient. Similar to shoulder and limb assessment, the clinician again examines the description of each of the stages and matches them based on his/her observation and impression.

2.2.2 Fugl-Meyer test

The Fugl-Meyer test [5] is a 226 point scale developed to evaluate patients recovering from hemiplegic (one sided lesion) stroke. It is divided into five domains: motor function, sensory function, balance, joint range of motion and joint pain. The
primary value of the Fugl-Meyer test is the 100-point motor domain which has received extensive evaluation.

Each domain consists of many items and each item is scored on a 3 point scale. A scale of zero implies the inability to perform, a score of one implies partial performance and a score of two implies full performance. The motor domain consists of many items measuring movement, coordination and reflex action about the shoulder, elbow, forearm, wrist, hand, hip, knee, and ankle. Similar to the Chedoke McMaster, the Fugl-Meyer test also involves physical and observational assessment by clinicians.

2.2.3 Purdue Pegboard test

The Purdue Pegboard test was initially used to test the level of hand and finger dexterity of workers in certain industrial jobs such as assembly, packing and operation of certain machines. More recently the test has been used in assessment of impairment caused by stroke [27].

The Purdue Pegboard consists of pins, collars and washers located in four cups at the top of a board. Below the cups and in the center of the board are two columns of holes, one for the right arm and the other for the left arm. There are different tests involved in assessment of stroke patients. For each test, the examiner verbally provides the subject with a set of standardized instructions on how to proceed.

The first test involves assessment of the right hand and left hand separately. The examiner instructs the subject to place only one type of object within the holes on the right column using the right hand, the subject is then given 30 seconds to fill as many holes on the right column with the specified object. The right hand score is then simply
the number of holes filled. The exact test is performed again for the left hand except the subject is required to fill the left column holes.

The second test involves the use of both hands to assemble a set of objects in a specific order. The subject is required to assemble objects using both hands in the right column and the number of objects assembled is a combined measure of the ability of working with both hands.

No reference exists for scores of normal and healthy individuals. Therefore, a normative data table is provided with the test and consists of a selection of employees of various industrial jobs that require manual work with the hands [4].

### 2.3 The Need for More Objective Tools of Assessment

In this subsection we first discuss the importance of effective assessment of upper limb impairment. We then discuss the limitations that are present in the current clinical assessment measures. Finally, we briefly review advances in robotics which motivates their use as clinical assessment devices for upper limb impairments.

#### 2.3.1 Importance of Assessment

The aim of stroke rehabilitation is to help the stroke survivor achieve the best possible recovery and promote independence after a stroke [28]. The current focus of research involves the design of rehabilitation techniques that maximize the extent and rapidity of functional recovery. Reducing the level of motor impairments requires information about the deficits that occur in motor control as a result of stroke. Success in this area has been limited likely as a result of insufficient information regarding the
characteristics of movement after stroke. Many researchers agree that to achieve successful rehabilitation therapy after stroke, the causes of the underlying motor impairments common to the patients must be well understood [29, 30].

2.3.2 Limitations of Current Assessment Tools

We do not question the validity of the different stages of classification of any of the clinical tests; rather we are concerned with the effectiveness of the clinical scores in aiding rehabilitation therapists. Many of the current clinical tools used in the measurement of recovery and assessment are inherently subjective as they depend on the clinician’s own observation and evaluation [1]. As noted earlier in the presentation of the Chedoke-McMaster method, the clinician either performs physical examination or requires the subject to carry out physical tasks.

The coarse rating system (Scores 1 to 7) may overcome variability due to a clinician’s own judgment. The problem then arises in the inability of these coarse ratings to capture minute or subtle changes in performance as a result of slight recovery. More objective tests like the Purdue-Pegboard can only measure a single dimension (hand dexterity). Furthermore, none of the current clinical assessment tools provide therapists or physicians with detailed kinematics of the underlying motor deficits (e.g. hand velocity).

There has been an interest in more advanced and objective clinical tools that could help better assess the level of impairment and the stage of recovery from stroke [40]. The tools should also be able to encompass more than one dimension (elbow and shoulder).
2.3.3 Advances in Robotics and their Potential in Clinical Assessment

While robots have been used to assist in rehabilitation [10, 11, 24, 25], there has also been an explosion in the use of robotic technologies for quantifying motor function for basic research. Robotic technologies have an obvious value for quantifying motor impairments as they objectively monitor how subjects perform at any given moment. Of particular interest is the robot’s ability to quantify even subtle degradations of motor performance across different experimental trials and different movement directions. Such differences are not visible to the naked eye. In our research we explored the use of a dual-arm robotic device (KINARM) in assessment of stroke and compared it to Chedoke-McMaster and Purdue Pegboard scores.
Chapter 3

Use of Robotics in Rehabilitation and Assessment

In this chapter we discuss robotic devices used in rehabilitation of upper limbs and the use of robots in assessment of upper limb impairments. Some of the figures in this Chapter were adapted with permission from Melanie Demmer’s Thesis [9].

3.1 Use of Robotic Technology in Rehabilitation

The use of robotic technologies for quantifying motor function has exploded in recent years. These devices have significantly enhanced the knowledge about the neural and mechanical basis of motor control [2, 18]. The successful use of such robots in research has shown potential for their use in a clinical setting.

With an increased demand on the healthcare system and limited resources, researchers were motivated to think about ways in which to optimise the quality and cost effectiveness of healthcare. Many robots have since been designed with the focus being on
rehabilitation uses. The robots were developed not to replace therapists, but rather to assist and support them in their efforts to facilitate a disabled individual's functional recovery.

The MIME (Mirror-image motion enabler) robot is used to move the affected arm in straight lines or in complex patterns, along a tabletop surface or in 3-dimensional space. The subject’s forearm movements can be passive (movement provided by the robot) or active-assisted (subject initiates movement, the robot provides any necessary assistance to the impaired arm to complete motion). MIME can take commands from the unaffected arm to help move the affected arm in a mirror-image pattern. This permits practice of bimanual movements to aid in recovery of muscle control. Studies done with MIME show that both robot assisted and unassisted stroke groups improved their ability to move the affected arm but the robot-assisted group showed faster recovery [25].

ARM Guide (Assisted Rehabilitation and Measurement Guide) was used to assist in recovery and investigate whether the mechanical assistance provided by the robot or the repetitive movement attempts made by the patients was the primarily stimulated recovery. The experiment showed comparable results between subjects who performed free reaching and subjects that underwent robot assisted reaching [31].

Though robots have been used extensively in rehabilitation, there have been limited attempts so far for their use as clinical assessment tools [40]. The MIME project [25] used the Fugl-Meyer test to assess the improvements in motor performance in patients and the ARM Guide [31] used Chedoke-Mcmaster in assessment. It would therefore be interesting to observe a robotic assessment system that is objective and able to capture subtle changes in motor performance. This would greatly assist rehabilitation therapists in their planning and execution of rehabilitation.
3.2 Use of Robotic Technology in Assessment

Although many studies were aimed at understanding upper limb impairments in stroke subjects, very few incorporated motion analysis [13,19,22]. In this subsection we review two studies in which each used a novel robotic system for the assessment of upper limb function of hemiparetic stroke patients.

3.2.1 Upper Extremity Kinematic Model

Setup:

A three-dimensional biomechanical model of the upper extremity (arm) was developed at Marquette University for quantification and assessment of stroke rehabilitation. The device consisted of five segments 1) left lower arm, 2) left upper arm, 3) right lower arm, 4) right upper arm, and 5) trunk. Markers were used to identify the segments and a motion tracking system was used to capture movement patterns [40].

Methods and results:

Subjects diagnosed with hemiparesis as a result of stroke performed a reaching task to an anterior target with both arms while seated on a table. Linear time analysis for the elbow angle and elbow angular velocity was analyzed for both arms. Statistical differences were found between the arm affected by stroke and the unaffected arm indicating the potential of the Upper Extremity Kinematic Model in assessment of upper limb impairment [40].
3.2.2 Uni-lateral Kinesiological Instrument for Normal and Altered Reaching Movement (KINARM)

A robotic single arm device called KINARM (Kinesiological Instrument for Normal and Altered Reaching Movements) has been developed by Scott’s group [2] at Queen’s University to study the activity of neurons during behavioral tasks in non-human primates. More recently the group developed different techniques and tasks for the KINARM that can quantify sensory and motor information. Since then the robot has been investigated by clinicians at St Mary’s at the Lake Hospital for its potential in assessment of upper limb impairments. As our current thesis involves the use of a similar dual arm KINARM system for assessment of stroke patients, we will review in more details a previous study that incorporated the single arm device in investigation of upper limb impairments of stroke patients.

Setup:

The robotic device consisted of a single-right arm exoskeleton system. Fiberglass braces fixed to a fully adjustable linkage were attached to the upper and lower segments of each arm. This permitted flexion and extension movements of the shoulder and elbow with the arm abducted in the horizontal plane. The robotic device was coupled to a virtual reality system such that the index finger tip and target positions were projected as small circles on a semi-transparent mirror through which subjects could see their entire limb.
CHAPTER 3. USE OF ROBOTICS IN REHABILITATION AND ASSESSMENT

Methods:

Control and stroke subjects were instructed to reach with their right arm to 16 peripheral targets from a center hold target as soon as the targets illuminate. 10 repeat trials were performed for each target (See Figure 3.1).

![Figure 3.1](image.png)

**Figure 3.1** View of unilateral-arm-KINARM reaching task. Subjects are instructed to reach to 16 targets at a 10 cm distance from the center target with their right arm.

Results:

Differences in reaching between control subjects and stroke subjects were observed. Furthermore, differences in reaching patterns based on lesion location were also observed indicating the potential for the KINARM system to detect impairments in reaching (See Figure 3.2).
CHAPTER 3. USE OF ROBOTICS IN REHABILITATION AND ASSESSMENT

Figure 3.2 Different reaching profiles for subjects with different lesion locations. Note that subject RC5 with a right cerebral lesion presented smooth movements similar to control subject C15, this is because their left arm was affected by the lesion.

Different parameters such as peak velocity of the hand and distance error from the target were calculated and linearly compared across all targets for all subjects. Some parameters showed good separation between control and stroke subjects while others provided less separation. These parameters also presented good correlation to clinical scores such as the Purdue Pegboard score and the Chedoke-McMaster score. It was then hypothesized that such parameters could be used in a clinical setting as good assessment measures for upper limb impairments due to stroke [9].
3.2.3 Limitations of Previous Assessment Devices

Upper Extremity Kinematic Model:

Clear statistical differences were observed for the elbow angle and elbow angular velocities between the affected arm and the unaffected arm for the stroke subjects studied [40]. However, no control subjects were included in the study and hence it is difficult to confirm that these results would not occur due to a subject being left handed or right handed.

Unilateral KINARM Device:

Comparing data from the right arm of control subjects directly to the impaired right arm of stroke subjects completely underestimated many variables that could result in noise. These variables include variability due to experimental setup and general variability in control subjects due to psychological and physiological conditions that can greatly differ.

As well, stroke usually causes a lesion on one side of the brain resulting in hemiparesis of the limb contralateral to the side of the lesion. Therefore, impairments of an affected left arm due to a lesion on the right side of the brain could not be studied using a single right-arm device. Finally, comparison of performance of the affected arm to that of the unaffected arm is not possible on a single-arm device.
Chapter 4

Methods

In this chapter we will review the population of control and stroke subjects studied. We then present in details the setup for the bilateral arm KINARM device used in our study. A review of the reaching task used to investigate upper limb movement of control and stroke subject is also presented. Finally parameter selection and data analysis techniques are presented.

4.1 Subjects Selected

The study involved 52 subjects: 19 stroke patients, and 33 control subjects. Stroke subjects were composed of two groups; 9 patients with lesions on the right hemisphere of the brain and a paretic left arm and 10 patients with lesions on the left hemisphere of the brain and a paretic right arm as diagnosed by clinicians.

Control subjects included in the study were of varying age (20-65 years old) and not age matched to stroke subjects. This was simply due to insufficient number of control subjects that were of age match to stroke subjects. Controls were provided with a detailed questionnaire regarding any injuries or medical treatments to ensure that they were free of
CHAPTER 4. METHODS

musculoskeletal and neurological conditions (See Appendix B). Stroke subjects at Saint Mary’s on the Lake Hospital were also provided with the questionnaire and were admitted to the study by clinicians given that they fulfilled the following selection criteria:

1) Hemiparesis resulting from stroke occurring at most 3-4 weeks prior to participation in the study,
2) Absence of notable sensory deficits in the paretic upper limb or of vision,
3) Absence of severe cognitive or affective dysfunction (mental health),
4) Absence of severe concurrent medical problems,
5) Absence of severe weakness or atrophy of the paretic limb, and
6) Capacity to complete the experimental protocol.

Due to severe impairments, muscle atrophy and weakness of an upper limb could occur as a result of prolonged and inadequate use by the patient. This in turn could mask the underlying deficits of the sensorimotor system that need to be fully understood by a clinician to plan an effective rehabilitation therapy [16]. Thus, as opposed to an earlier study with a unilateral-KINARM device [9], where patients were admitted at least 6 months after the occurrence of stroke, our study aims at capturing the upper limb impairments at their earliest stage.
4.2 Bi-lateral KINARM Device

In this subsection we discuss in details the setup of the robotic device used in our study. We also discuss the reaching task that subjects are required to perform and the subsequent methods applied in our data analysis.

4.2.1 Robotic Setup

Our experimental device consisted of a robotic bilateral-arm exoskeleton device (BKIN Technologies Ltd., Kingston, Canada; Scott 1999). Fiberglass braces fixed to a fully adjustable linkage were attached to the upper and lower segments of each arm (See Figure 4.1). This permitted flexion and extension movements of the shoulder and elbow with the arm abducted into the horizontal plane [3,39].

The robotic device was coupled to a virtual reality system such that index finger tip and target positions were projected as small circles on a semi-transparent mirror (See Figure 4.1) through which subjects could see their entire limb. Finger tip position and velocity during a reaching task are recorded [3,39].
CHAPTER 4. METHODS

Image from projector is reflected onto a semi-transparent mirror

Figure 4.1 View of the bilateral-arm KINARM device used in our study.
4.2.2 Center-Out Reaching task

All subjects underwent the center-out reaching task on the bilateral KINARM device with both arms. This task was designed to measure motor performance and entails the subject moving their arm on a horizontal plane from a center hold position to 8 virtual targets displayed on a semi-transparent mirror (See Figure 4.2). The starting position (1cm diameter at fingertip) of the left and right hands were equally separated from the midline by 6-8cm giving shoulder and elbow angles of 30 and 90 degrees, respectively. The target position for each hand was 10 cm forward from the start position (See Figure 4.2).

For each reaching trial the subject was required to match their finger tip position with a target position as soon as the target would illuminate. Eight repeat trials were performed for each target. The order of target presentation however was not sequential. Three seconds were given to complete a single reaching trial and data recording stops after three seconds pass. If a subject completes the trial in a time frame less than three seconds then they are to maintain their hand in the peripheral target location until the peripheral target light goes off.

Two more trials for each target called catch trials were also performed. A catch trial is simply the illumination of the center hold target and thus would require the subject to maintain their hand at the center target rather than reach for a peripheral target. This process was designed to deter subjects from learning or guessing target locations. It is important to note however that no data from the catch trials were used in any of our analysis.
Figure 4.2. The center-out reaching task on the bilateral-arm-KINARM device. A. The subject moves his/her hand to one of eight targets from the center hold position (fingertip) once the target light comes on. B. Targets used in our current work on the bilateral system.
4.3 Parameters Selected for Analysis

Reaction time and first peak velocity of the hand (See Figure 4.3) were selected for our investigation. In this subsection we present details of parameter description, parameter calculation and handling of noise.

**Figure 4.3** Hand velocity profiles for the reaching task.  
**A**. A normal reach trial by a control subject with no major corrective movements. PTON is the time point at which the peripheral target light illuminates. MON is the point at which the subject starts moving (Movement Onset) and MOFF is the point at which the subject stops moving (Movement Offset). Reaction time (ReacTime) is the time gap between target illumination and subject response. FPVEL is the first peak velocity of the hand and indicates the speed of the initial movement. Total Movement Time is the time between Movement Onset and Movement Offset.  
**B**. A reach trial by a stroke subject with four major corrective movements.
4.3.1 Parameter Description

*Reaction time* measures the response time of a subject to a stimulus. Theoretically, *reaction time* measures the sensory capacity of the brain to detect a stimulus and the processing time involved in planning and initiating a response. This theoretical aspect of brain processing is referred to as open loop processing [15, 33, 35]. Closed loop processing relates to online control and the mechanism which uses feedback to guide the limb in reaching to a spatial target [33, 35].

An algorithm for automated detection of movement onset was recently developed by Scott’s group [9]. This allowed for the calculation of *reaction time* (See Figure 4.3). Movement offset on the other hand has not been automated. Therefore, parameters that could measure the closed loop component could not be calculated (example, Total Movement Time). We expect that stroke subjects with a lesion affecting the open loop processing will present a higher *reaction time* value (Slower response).

*First peak velocity* of the hand measures the speed of the initial movement. If a subject can only initiate slow movements then this parameter should capture such impairment.

4.3.2 Parameter Calculation and Handling of Noise

Lab technicians have reported that sometimes control subjects lose interest or motivation due to the lengthy process involved. This could result in a different response for one or two trials and therefore a different parameter value that would be considered as noise. Thus, for each parameter the median value for all trials to each target was
computed. We were mainly interested in the median value of a parameter as it is insensitive to the noise that could be caused by lack of interest and loss of focus.

When calculating our median parameter value we included trials where the subject initiated a movement but could not successfully reach the target. If no movement occurred for all trials to a given target, the median value of reaction time and first peak velocity would be zero. A zero value for first peak velocity implies that a subject’s hand remained at the center target for all trials and no attempt was made to reach for the peripheral target. For reaction time on the other hand, a zero value could imply an instantaneous response by the subject to all trials as soon as the target illuminates which is not possible. After carefully examining our data we determined that longest reaction time point was less than but close to 1000 milliseconds. We thus replaced any zero data point for median reaction time with a value of 1000 milliseconds.

4.4 Parameter investigation using Traditional Analysis

In Section 3.2 we discussed briefly previous analysis using the Unilateral KINARM device. Previous work incorporated reaching diagrams to investigate differences in reaching between control and stroke subjects. As well, linear analysis of various parameters was used to investigate the potential of each parameter at separating control and stroke subjects. In our work we employ similar traditional methods of analysis.

Linear diagrams were generated with the parameter value across all targets for each subject. Control and stroke subjects were properly labeled. Since our goal was to identify separation between both groups we calculated the mean and standard deviation
for control subjects. Since most data for controls (95%) would lie within two standard deviation units (*empirical rule*), we counted stroke subjects that fell out of the control range. We used the following equation to test if a data point for a stroke subject was more than two standard deviation units from the control average.

\[
\frac{\text{Given Median Value} - \text{Control Average Median Value}}{\text{Standard Deviation of Control Median Value}}
\]

This then served as an evaluation of the ability of each parameter at successfully separating control and stroke subjects.

### 4.5 Parameter Investigation using New Analysis Techniques

In our new methods of analysis we design a new visual tool to quantify the reaching performance for each target. This is then proposed as a new assessment tool that could be used by clinicians to quickly screen through the profiles of all subjects.

As well, new parameter investigation technique that is based on comparing data from both arms is employed. Correlation analysis is then used to correlate current clinical scores to our summarized parameters to identify if our parameters capture similar impairments. Finally a data clustering method (hierarchical clustering) was used to investigate the potential of the *reaction time* parameter and the *first peak velocity* parameter at separating control and stroke subjects.
4.6 Review of Hierarchical Clustering

Hierarchical clustering is a method used in grouping data [34]. This clustering method uses a tree structure where two clusters at each level are joined to form clusters at the next higher level. The goal of this clustering is to group objects that are close together and form subgroups such that objects in each subgroup are the most similar to each other.

Steps of the algorithm:

1) Find the similarity metric between all possible combinations of pairs of objects. Here different methods could be used to calculate similarity. For the purpose of our research we used the simple Euclidean Distance rule. If an object has more than one element then there are different ways of calculating the distance between the two objects. In Single Linkage simply the smallest distance between any two points in the two objects is used. In Complete Linkage the maximum distance is used and in Average Linkage the average distance is used. There are other different linking techniques that were developed but for the purpose of our research we used Average Linkage.

2) The two closest objects are linked together as a cluster. Each object is deleted from the list and a new object is formed as a combination of the two old objects. Step one is executed again until one object remains.

To help illustrate how this method works, in MATLAB we generated three groups of 10 three dimensional (a, b and c) points at random where each point is in the range of 0-1. For the first group we added a value of one to each coordinate (a+1, b+1, c+1) and to
the following group two was added and three was added to the coordinates of the third group. The three groups would thus have a normal distribution about a mean value and they would be separated due to the difference added. We generated the hierarchical cluster tree diagram (*Dendrogram*) in MATLAB to observe how the clusters show with our technique (See Figure 4.4).

![Dendrogram](image)

**Figure 4.4** Dendrogram generated through hierarchical clustering. The leaves of the tree represent the cluster points. The vertical axis represents the distance between clusters points. I (points 11-20), II (points 21-30) and III (points 1-10) represent our three clusters.

An extra step is performed in the hierarchical tree to generate clusters based on user preference. This step is performed using a MATLAB clustering algorithm. For the
purposes of our work we arbitrarily chose three clusters since our subject pool consists of three classes (control, affected right arm and affected left arm). This algorithm has an advantage in that it provides the user with the power of choosing how many clusters are to be visualized from the tree. Based on the number of clusters that the user chooses, the algorithm splits the tree by drawing a horizontal line that crosses a number of vertical lines equal to the number of clusters chosen by the user. A silhouette plot is then generated for the chosen clusters. The silhouette value for each point is a measure of how similar that point is to points in its own cluster compared to points in other clusters thus it acts to show the consistency of similarity of points within a cluster.
Chapter 5

Traditional Analysis

In this section we present a linear parameter analysis of reaction time and first peak velocity. In our analysis we mainly examine the potential of each parameter at separating control and stroke subjects. We also compare some of our results to results from related research.

5.1 Clinical Scores for Stroke subjects

We first investigated two clinical scores for our stroke subjects. Chedoke Arm score and Purdue Hand score (See Section 3) were recorded for seven of ten subjects with an affected right arm and six of nine with an affected left arm.

Figure 5.1 depicts a comparison of the left and right arm scores for the Purdue Pegboard and Chedoke McMaster tests. Four of seven subjects with an Affected Right Arm presented a low Purdue hand score for the right arm (< 5) while only two subjects presented a low Chedoke Arm score (< 2) for the right arm. All six subjects with an Affected Left Arm presented a low Purdue hand score (< 5) with their left arm. For the Chedoke Arm score, all subjects with an Affected Left Arm presented a score below seven for the left arm. In general, both stroke groups presented high clinical scores with
their non-affected arm. As well, more subjects with an Affected Right Arm presented higher clinical scores with their impaired arm as compared to subjects with an Affected Left Arm.

Figure 5.1 Clinical scores for both arms of some stroke subjects. Note that some subjects have similar scores Purdue and Chedoke scores.

### 5.2 Reaching Profiles

For each reaching trial, about 40 different data values are recorded each millisecond for the length of the trial (three seconds). The data is then stored in a scientific database using DB2. Drivers for connecting to DB2 and executing SQL queries in Matlab running environment have been developed [14]. Scripts were developed to generate a visual illustration of all eight reaches to all eight targets for each arm. It is expected that control subjects will show smooth and straight hand trajectories to the peripheral targets while stroke subjects might show different trajectories with their
CHAPTER 5. TRADITIONAL ANALYSIS

impaired limb due to muscular or visual impairments. To confirm such expectations we selected randomly a control subject (DB), a subject with an Affected Right Arm (AJ) and a subject with an Affected Left Arm (FC). Visual illustrations of hand trajectories during reaching were then generated for both arms of each of these subjects (results displayed in Figure 5.2).

Control subject DB showed smooth and straight hand trajectories for most trials and all targets of both arms. Subject AJ presented less straight hand trajectories with impaired right arm as compared to their non-affected left arm. Subject FC also showed jerky movements especially for a few targets (225 and 270 degrees) with the impaired arm while straight trajectories were visible with the non-affected right arm.

Diagrams displaying hand trajectories therefore present the potential of identifying targets where difficulties in reaching are present. However, no scores reflecting reaching performance are present and careful examination of the hand trajectory profile is required to properly identify targets where the most impairment in reaching is visible. In Section 6 we present a new diagram that contains quantitative data related to reaching performance.

5.3 Reaction Time (Traditional Analysis)

Through a linear analysis of each parameter, we were interested in observing separation of control subjects and stroke subjects in order to get an indication of their potential as good assessment tools. For both parameters, a simple linear diagram was used to view the median parameter value across all targets for a given arm.
CHAPTER 5. TRADITIONAL ANALYSIS

We generated one figure for each arm to analyze median reaction time across all targets for all subjects. All targets were listed on the horizontal axis in an anti-clockwise fashion starting from Target 7 (270 degrees) onwards (See Figure 5.3).

Figure 5.2 Reaching profiles of three subjects.
Figure 5.3 Median reaction time for both arms of all subjects across all spatial targets.

Figure 5.3 depicts the median reaction time of all subjects across all targets for the left and right arm. Some subjects with an Affected Left Arm presented a visibly longer
reaction time with their paretic arm for some targets as compared to control subjects. Some subjects with an Affected Right Arm also presented a slightly longer reaction time with their right arm for some targets as compared to control subjects. Paradoxically two subjects with an Affected Right Arm presented a shorter reaction time with their paretic right arm as compared to control subjects across all targets. To better our understanding of the results from Figure 5.5 we formulated a table with mean and standard deviation values for control subjects, subjects with an Affected Right Arm and subjects with an Affected Left Arm (See Table 5.1).

<table>
<thead>
<tr>
<th></th>
<th>Control (n=33)</th>
<th>Affected Right Arm (n=10)</th>
<th>Affected Left Arm (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Group Value (milliseconds)</td>
<td>Group Standard Deviation (milliseconds)</td>
<td>Average Group Value (milliseconds)</td>
</tr>
<tr>
<td>Right Arm</td>
<td>365.8</td>
<td>67.9</td>
<td>374.6</td>
</tr>
<tr>
<td>Left Arm</td>
<td>367.9</td>
<td>54.4</td>
<td>364.8</td>
</tr>
</tbody>
</table>

Table 5.1 Average and standard deviation value of median reaction time for each subject group.

Table 5.1 depicts the average and standard deviation of median reaction time for control subjects, subjects with an Affected Right Arm and subjects with an Affected Left Arm. In Table 5.1 subjects with an Affected Right Arm presented a similar average reaction time value to control subjects for both arms. The standard deviation, however, was higher for subjects with an Affected Right Arm indicating more variability than that of control subjects. To test the significance of the similarity in means we assumed that control subjects and subjects with an Affected Right Arm come from normal distributions with unknown and possibly unequal variances. We then applied a non-pooled t-test
(ttest2.m in Matlab) for each arm with the null hypothesis being that both means are equal. With a significance of 0.05 the null hypothesis was accepted for both arms indicating the significance in the similarity observed.

Subjects with an Affected Left Arm presented a higher average reaction time as compared to control subjects for both arms. The standard deviation was also higher indicating more variability than that of control subjects. Again we applied a non-pooled t-test with the null hypothesis being that the mean of subjects with an Affected Left Arm is higher than that of control subjects. The null hypothesis was rejected for the impaired left arm (mean is higher by chance) and accepted for the non-impaired right arm with a significance of 0.05. The varying level of impairment and the small sample size of our stroke subjects present a challenge at analyzing statistical group differences. However, can we reliably separate out stroke subjects based on the delayed response (longer reaction time) observed for some subjects?

To assess the potential of the reaction time parameter at separating control and stroke subjects, we calculated the difference between a stroke subject’s median reaction time and the average median value for control subjects. The difference was then normalized using the control standard deviation (See Section 4.4.1). Assuming a normal distribution for control subjects, the empirical rule states that about 95% of the control data is within two standard deviation units from the mean. We were therefore interested in reaction time values that were above two control standard deviation units. This would indicate the presence of impairment in reaction time to a stimulus. Our results are displayed in Table 5.2.
### Table 5.2

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>Target</th>
<th>270</th>
<th>315</th>
<th>0</th>
<th>45</th>
<th>90</th>
<th>135</th>
<th>180</th>
<th>225</th>
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<tr>
<td><strong>Affected Right Arm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(n=10)</td>
<td>Right Arm</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
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<tr>
<td></td>
<td>Left Arm</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Affected Left Arm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(n=9)</td>
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<td>1</td>
<td>1</td>
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</tr>
<tr>
<td></td>
<td>Left Arm</td>
<td>8</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 5.2 Number of stroke subjects whose reaction time differed from control subjects by 2 standard deviation units.

Table 5.2 displays for each stroke group and across all targets, the number of subjects with a longer reaction time than the control average (greater than two standard deviation units). In Table 5.2 we note that some stroke subjects for each group are separated for some targets over others. In general, the arm affected by stroke presented more separation for the given stroke group. It is also important to note that more subjects with an Affected Left Arm are separated using data from their paretic arm as compared to subjects with an Affected Right Arm. This implies that more subjects with an Affected Left Arm present impairment in reaction time to a stimulus as compared to subjects with an Affected Right Arm.
5.4 First Peak Velocity (Traditional Analysis)

![Graph showing median first peak velocity for both arms of all subjects across all spatial targets.](image)

**Figure 5.4** Median first peak velocity for both arms of all subjects across all spatial targets.

Figure 5.6 depicts *first peak velocity* for all subjects across all targets. Interestingly a general pattern is observed for control subjects. For the left arm a high
median first peak velocity value is observed at targets 315 and 135 degrees and for the right arm a high median first peak velocity value is observed for targets 225 and 45 degrees. These targets for both arms are ones where a subject is required to extend their elbow away from the trunk and flex their elbow towards the trunk respectively. Four of nine subjects with an Affected Left Arm present a clearly lower first peak velocity with their impaired left arm as compared to control subjects. Unexpectedly, one subject with an Affected Right Arm seems to present a higher first peak velocity with both arms as compared to control subjects.

Once again we were interested in calculating general statistical values (mean and standard deviation) for each of our subject groups (See Table 5.3)

<table>
<thead>
<tr>
<th></th>
<th>Control (n=33)</th>
<th>Affected Right Arm (n=10)</th>
<th>Affected Left Arm (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Group Value (mm/s)</td>
<td>Group Standard Deviation</td>
<td>Average Group Value (mm/s)</td>
<td>Group Standard Deviation</td>
</tr>
<tr>
<td>Right Arm</td>
<td>25</td>
<td>5.5</td>
<td>24</td>
</tr>
<tr>
<td>Left Arm</td>
<td>25</td>
<td>5.7</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 5.3 Average and standard deviation value of median first peak velocity for each subject group.

Table 5.3 presents the mean and standard deviation of first peak velocity for control subjects, subjects with an Affected Left Arm and subjects with an Affected Right Arm. Subjects with an Affected Right Arm show an average first peak velocity that is very close to that of control subjects for both arms. Standard deviation however, was higher for both arms indicating more variability than control subjects. Through the
application of a t-test we were able to accept the null hypothesis of the similarity in means with a significance of 0.05 for both arms.

Subjects with an Affected Left Arm presented a lower average first peak velocity as compared to control subjects. Group standard deviation was found to be higher than control standard deviation only for the left arm. The application of a t-test allowed for accepting the null hypothesis of the observed lower mean with a significance of 0.05 for both arms. Again due to the limitation in sample size of stroke subjects, we were interested in their linear separation from control subjects. This time however, we were interested in first peak velocity values that were more than two standard deviation units below the control average. This would therefore imply impairment in the ability to generate a fast initial reaching movement.

<table>
<thead>
<tr>
<th>Number of separated Stroke subjects for each target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject Group</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Affected Right Arm (n=10)</td>
</tr>
<tr>
<td>Right Arm</td>
</tr>
<tr>
<td>Left Arm</td>
</tr>
<tr>
<td>Affected Left Arm (n=9)</td>
</tr>
<tr>
<td>Right Arm</td>
</tr>
<tr>
<td>Left Arm</td>
</tr>
</tbody>
</table>

Table 5.4 Number of stroke subjects whose first peak velocity differed from control subjects by 2 standard deviation units.

Table 5.4 displays for each stroke group and across all targets, the number of subjects with a lower first peak velocity than the control average (more than two standard deviation units below the control average). Some subjects with an Affected Right Arm
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were separated over some targets through the analysis of the right arm. However, no subjects were separated through the analysis of the left arm. In other words, all subjects with an Affected Right Arm presented first peak velocity within the control range with their non impaired arm.

Some subjects with an Affected Left Arm were separated for some targets through the analysis of both arms. This therefore indicates that some subjects with an Affected Left Arm presented first peak velocity that was lower than the control range with their non affected right arm. Similar to analysis of reaction time, more subjects with an Affected Left Arm were separated using data from their paretic arm as compared to subjects with an Affected Right Arm. In other words, more subjects with an Affected Left Arm presented impairment in generating a fast initial movement as compared to subjects with an Affected Right Arm

5.5 Summary of Results

In this subsection we first discuss the results of two relevant studies that analyzed reaction time and first peak velocity for a reaching task in stroke groups with unilateral upper-limb impairments. Our results are then contrasted with those of the two selected studies and finally a brief summary of our results through traditional linear analysis are presented.
5.5.1 Results from relevant research

In the study carried out by Haaland and Harrington, stroke patient groups with a left hemisphere lesion and a right hemisphere lesion performed a visually guided reaching task and data was analyzed for movements with their ipsilesional arm [35].

The main goal of the study was to record the effect of the brain lesion on reaction time and initial velocity of reaching. It was determined that while the right-hemisphere lesion group presented a longer reaction time, their kinematic parameters including instantaneous velocity (first peak velocity) were similar to the control group. On the other hand, while the left-hemisphere lesion group did not differ in their reaction time a lower value for first peak velocity was observed.

Another study by Haaland et al. involved a similar group of patients with another visually guided reaching task [33]. Similar to the previous study, parameters were analyzed for the ipsilesional arm. The right-hemisphere group presented no deficits in reaction time or in first peak velocity. The left-hemisphere group presented a longer reaction time and a lower first peak velocity.

Both studies were selected as they analyzed the same two parameters for a similar reaching task to that of our study. We summarize our results (Tables 5.1 and 5.3) for the unaffected arm of both patient groups alongside the results from the two studies two tables (one for each parameter) to allow for easy comparison across the three studies (See Tables 5.5 and 5.6).

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1 Remember that a right hemisphere lesion in the brain will most likely result in a paretic left arm and vice versa.
CHAPTER 5. TRADITIONAL ANALYSIS

<table>
<thead>
<tr>
<th>Reaction Time (Ipsilesional Arm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke Group</td>
</tr>
<tr>
<td>Left Hemisphere Lesion</td>
</tr>
<tr>
<td>Study 1</td>
</tr>
<tr>
<td>Study 2</td>
</tr>
<tr>
<td>Our Results</td>
</tr>
</tbody>
</table>

Table 5.5 Comparison of results from linear analysis of reaction time with related work.

<table>
<thead>
<tr>
<th>First Peak Velocity (Ipsilesional Arm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke Group</td>
</tr>
<tr>
<td>Left Hemisphere Lesion</td>
</tr>
<tr>
<td>Study 1</td>
</tr>
<tr>
<td>Study 2</td>
</tr>
<tr>
<td>Thesis Results</td>
</tr>
</tbody>
</table>

Table 5.6 Comparison of results from linear analysis of first peak velocity with related work.

Tables 5.5 and 5.6 both present a comparison of results from three studies analyzing reaction time and first peak velocity respectively. Thesis results for reaction time agree with the first study. The results for first peak velocity on the other hand are completely opposite to that of both studies. Differences in the characteristics of patient population (lesion size, specific location, etc.) could be the reason for the differences in results observed.
5.5.2 Summary of Traditional Analysis

Linear diagrams (Figures 5.3 and 5.4) present some separation of stroke subjects for some targets over others. However, it is difficult to properly understand the underlying impairment simply by examining the linear diagram. Stroke subjects who might be unaware (hemineglect) or cannot see (visual impairment) one or few targets could show poor performance in reaching to these targets. As well, stroke subjects who cannot perform a reach due to specific muscle impairment (e.g. difficulty in extending their elbow) are also likely to perform poorly when moving to targets where the impaired muscle is mostly involved. It is therefore hard to understand from traditional linear diagrams the underlying impairment that best explains the poor performance in reaching for stroke patients. In Section 7 we present new comparative methods that use data from both arms to help better understand underlying impairments in reaching.
Chapter 6

New Computational Methods and Results

In this chapter we first present a new reaching diagram that could serve as a complimentary assessment tool to the traditional reaching diagram in Section 5.1. We then present a new visualization technique that compares data for both arms and is based on our prediction of the likely cause of reaching impairments. Correlation of our results with clinical scores is then presented. Finally, a clustering technique (hierarchical clustering) is applied to our new summarized data to investigate the potential of separating control and stroke subjects.

6.1 New Visual Diagnostic Tool (% Trial Success)

In Section 5.1 we used a traditional reaching diagram to investigate differences between the reaching profiles of control and stroke subjects (See Figures 5.1, 5.2, 5.3). To better quantify the ability of completing all trials successfully we considered a trial to be unsuccessful if the subject could not reach the peripheral target (2cm in diameter and
10 cm from the center hold target) by the end of the three second period given for trial completion.

A new visual tool was then designed to aid in visualizing targets where not all trials were successfully completed. The tool consists of an octagon that contains 8 equally spaced triangular spaces representing the eight targets to which a subject reaches. If a subject completes all trials of an experiment (8 or 10) for a given target, then the color assigned to the space representing the target is white (100%). The fewer the trials that are completed to a target, the darker the color is to the space that corresponds to that target. The percent numeric value of trial completion is also shown in the space. This visual illustration would then act as a quick diagnostic tool in identifying targets where subjects present a low performance in reaching (See Figures 6.1, 6.2, 6.3 and 6.4). Note that if a subject could not perform any reach for a given target then 0% completion will be represented by a black color.

Figure 6.1 shows the reaching performance of two control subjects (BV and DB). Subject BV completed all reaching trials to all targets with both arms. Subject DB completed all reaching trials to all targets with both arms except for the left arm where one trial was not completed for a single target (0 degrees).

Reaching performance by two subjects with an Affected Right Arm (BS and MS) is shown in Figure 6.2. Both subjects completed successfully all reaching trials to all targets with their unimpaired left arm. Subject MS is observed to have darker targets as compared to subject BS for the impaired right arm. This indicates that subject MS could have more severe upper limb reaching impairments as compared to subject BS.
Figure 6.1 Trial completion diagrams for two control subjects. Numbers in spaces represent % trial completion. Subject DB appears to have unsuccessfully completed one trial for target 0 degrees of the left arm.
Figure 6.2 Trial completion diagrams for two subjects with an Affected Right Arm. Subject BS shows minimal impairments in some targets with the right arm whereas subject MS shows more severe impairments in most targets with the right arm specifically the target at 90 degrees.
Figure 6.3 Trial completion diagrams for two subjects with an Affected Left Arm. Subject JYS presents what seems to be a spatial neglect problem in movements to the left with both arms while subject DF only shows impairments in reaching to two targets with the left arm (270 and 315 Degrees).
Two subjects with an Affected Left Arm (DF and JYS) are presented in Figure 6.3. Subject DF appears to have good performance with the un-impaired right arm as only one target presented a slightly darker color (87.5% completion). When reaching with the left arm, subject DF was able to complete all trials successfully to most targets except targets at 270 and 315 degrees where he/she did not complete a single trial. It is hard to predict the possible cause of such impairment as the subject might have not been able to see the target (visual impairment) or simply had a muscular impairment that did not allow him/her to flex the elbow properly to reach the target. Subject JYS seems to present spatial neglect as reaching performance was observed to be lower for movements to the left as compared to movements to the right for both arms. In the following we present a summarized version of our new reaching diagrams for all stroke subjects and some control subjects (See Figure 6.4).

In Figure 6.4 we note that some (five) control subjects missed one trial to a single target when reaching with the left arm. Control subjects were free of musculoskeletal and neurological conditions. Loss of focus of some control subjects due to lack of interest or motivation is therefore the likely explanation for the few unsuccessful trials noted. This explanation has also been confirmed by technicians who have reported loss of focus or lack of interest of some subjects due to the lengthy process involved. Five subjects with an Affected Right Arm completed all trials to all targets successfully with their right arm (Figure 6.4) and only one subject with an Affected Left Arm was able to successfully complete all trials to all targets with their left arm.
**Figure 6.4** Trial completion diagrams for all stroke subjects and ten control subjects. Darker colors imply fewer trials completed successfully.
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This new visualization tool for trial completion could also be used in the future in a similar setting as that of Figure 6.4 to group all subjects with a similar lesion in the brain. The goal would then be to visually mine for targets where impairments are common.

However, this new tool does not show the hand trajectories that are visible through the previous diagrams (See Section 5). Differences in hand trajectories while reaching have been suggested earlier to be related to the brain lesion location [9]. We therefore suggest that our tool be used as a compliment rather than a substitute to the early diagram used for the analysis of reaching.

6.2 New Parameter Investigation Techniques

In this subsection two impairment frameworks are presented and applied to our new analysis of reaction time and first peak velocity.

6.2.1 New Analysis of Reaction Time

We first review possible impairments in reaching that could be used in our parameter analysis. Deficits in reaching can be due to impairments related to the spatial or motoric (muscular) aspects of the reaching task. Correspondingly, we have examined patterns of movement based on two frameworks.

6.2.1.1 Spatial Frame:

First, errors in performance were categorized based on the spatial direction of movement. The hypothesis is that certain impairments will be best characterized by
contrasting the spatial direction of movement. With this hypothesis we also assume that even though the motion of the left arm is a mirror image of the right arm, there is no need to superimpose targets when comparing parameter values between both arms. For example, if a subject reaches to target 2 (45 degrees) with either arms they are in effect moving towards the same spatial direction (See Figure 6.5).

We expect that the Spatial Frame would show impairments such as spatial neglect. Unilateral spatial neglect (commonly caused by stroke) is a condition which impairs a person's ability to look, listen or make movements in one half of their environment [41].

To calculate our parameter values using the Spatial Frame, the average median parameter value was calculated for all targets that represented movement to the right space (315, 0 and 45 degrees) and movement to the left space (135, 180 and 225 degrees). These average values were then labeled Right Movement and Left Movement respectively.

**Figure 6.5** View of the Spatial Frame. Target 2 for both arms involves movement to the right space whereas target 4 for both arms involves movement to the left space.
In the following we present results of analysis of reaction time using the newly developed Spatial Frame. Note that in our analysis of both reaction time and first peak velocity we will mainly state observations from generated figures.

**Figure 6.6** Analysis of reaction time with the Spatial Frame. First row plots (A and B) represent a comparison of each spatial movement between both arms. Second row plots (C and D) represent a comparison between both spatial movements of each arm. Rc, Rr and Rl are correlation values for the control group, subjects with an Affected Right Arm and subjects with an Affected Left Arm respectively. Note that each diagonal line represents the line Y=X.

Figure 6.6A depicts a comparison of movements to the left for both arms of all subjects. As noted earlier in Section 5 (See Figures 5.5 and 5.6), control subjects
presented a range of reaction times for both arms. However, reaction time was similar for both arms as most data points for control subjects are located close to the line Y=X. As a group, correlation of both arms was at a high of 0.89 indicating higher consistency in reaction time for movement to the left between both arms. In other words if a control subject presented a fast response with their right arm, they also tended to respond as fast with their left arm. Note that one control subject presented a long reaction time for movement to the left particularly with the right arm.

Seven out of nine subjects with an Affected Left Arm presented a longer reaction time with their left arm as opposed to their right arm as represented by data points above the line Y=X in Figure 6.7A. This implies that most subjects with an Affected Left Arm were slower in response for movements to the left, mainly with their impaired left arm. This was not just a systematic increase in reaction time for the left arm as there was no correlation between reaction time for the left and right arms (R=-0.001). Note that only one subject presented a slower response with their right arm. Subjects with an Affected Right Arm presented high correlation as a group (R=0.84) indicating higher consistency of reaction time for both arms. However, three of ten subjects presented a slightly longer reaction time with their right arm. Paradoxically two subjects showed a slightly faster reaction time than control subjects.

Figure 6.6B shows a similar comparative analysis of movements to the right space (Right Movement) with both arms. Again, control subjects presented high similarity (symmetry) for both arms and a high correlation of 0.85. Note that a couple of subjects fall out of the main control cluster due to a longer reaction time than other control subjects. Some subjects with an Affected Left Arm presented longer reaction time with
their left arm as opposed to their right arm, this break in symmetry is also the likely cause for the low correlation observed (R=0.43). Subjects with an Affected Right Arm presented high symmetry for both arms and a high correlation of 0.94.

It is interesting to note that a higher correlation for the control group can be attained through a different analysis frame than that of Figure 6.6A and 6.6B. In Figures 6.6C and 6.6D we reverse our analysis and compare movements to the left and right space for each arm. The correlations of both movements for each individual arm of control subjects in Figures 6.6C and 6.6D were 0.91 and 0.95 respectively. This value in consistency of reaction time for both movements of a given arm is higher than our previous analysis that correlated both arms for an individual movement.

When analyzing the left arm in Figure 6.6C, only three of nine subjects with an Affected Left Arm presented similarity in reaction time for both movements as shown by three data points lying close to the line Y=X. A low correlation (0.08) is also an indication of high variability in reaction time across those subjects. We note that four subjects presented a longer reaction time for movements to the left and two subjects presented a longer reaction time for movements to the right. Subjects with an Affected Right Arm however, presented more similarly in response to both movements with their left arm as most data points are close to the line Y=X. As well, these subjects presented a high group correlation of 0.80 indicating consistency in reaction time for both movements.

When analyzing the right hand (Figure 6.6D), only two of nine subjects with an Affected Left Arm presented a slightly longer reaction for movements to the left as
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compared to movements to the right. All other subjects (seven) were symmetrical in their response behavior to movements in both directions. Subjects with an Affected Left Arm as a group presented a high correlation of 0.91 indicating a high consistency in reaction time for both movements. Although subjects with an Affected Right arm showed a high consistency (R=0.8) in reaction time for both movements, five of ten subjects presented slightly longer response time for movements to the right as opposed to movements to the left (points lie below the line Y=X).

6.2.1.2 Muscular Frame:

Here we expect that impairments in reaching can be observed by comparing how movements of the left and right arms require the same muscle groups. Figure 6.7 illustrates that elbow extension of the left arm is active for movements to target 4 while elbow extension of the right arm is active for movements to target 2. Thus, in the Muscular Frame we superimposed four targets between both arms to compare parameter values during Elbow Extension, Elbow Flexion, Shoulder Extension and Shoulder Flexion. See results of analysis of reaction time in Figure 6.8.

Figure 6.7 View of the Muscular Frame. Elbow Extension for right arm occurs at target 2 and for left arm occurs at target 4.
Figure 6.8 Analysis of reaction time with the Muscular Frame. Left column plots (A and C) represent a comparison of movements around the elbow for both arms and right column plots (B and D) represent a comparison of movements around the shoulder for both arms. Rc, Rr and Rl are correlation values for control subjects, subjects with an Affected Left Arm and subjects with an Affected Right Arm respectively. Note that each diagonal line represents the line Y=X.

Figure 6.8 depicts a comparison of reaction time with the left and right arm for each of four dominant muscle groups (Elbow Extension, Shoulder Flexion, Elbow Flexion and Shoulder Extension respectively). First it is important to note that as a group, control subjects presented lower correlation for the left and right arm as compared to results with the Spatial Frame (See Figures 6.8A and 6.8B). This therefore indicates more
group inconsistencies in *reaction time* for the left and right arm when comparing muscle movements rather than spatial movements.

In Figure 6.8A six of nine subjects with an Affected Left Arm presented a longer *reaction time* with extension of their left elbow as compared to extension of their right elbow. However, a low correlation score ($R=-0.32$) between the left and right arm indicates that the increase of *reaction time* for the left arm is not systematic. Subjects with an Affected Right Arm presented a correlation score of 0.72 indicating higher group consistency in *reaction time* for both arms as compared to subjects with an Affected Left Arm. Paradoxically one subject with an Affected Right Arm is noted to have a slower response with their left arm as compared to their right arm while extending their elbow.

When analyzing *reaction time* for Shoulder Flexion (Figure 6.8B) of both arms we note that four of nine subjects with an Affected Left Arm fell below the line $Y=X$, indicating a longer *reaction time* with their unaffected right arm. One subject was above the line $Y=X$ indicating longer *reaction time* with their affected left arm while three subjects were close to the line $Y=X$ indicating similar *reaction time* with both arms. Correlation was at a low of -0.23 indicating inconsistency of *reaction time* for both arms of subjects with an Affected Left Arm. Seven of ten subjects with an Affected Right Arm also presented a slightly longer *reaction time* with their unaffected left arm. Correlation for these subjects was at a high of 0.84 indicating consistency in *reaction time* for both arms.

Figure 6.8C presents *reaction times* at Elbow Flexion for the left and right arm. Five of ten subjects with an Affected Left Arm are above the line $Y=X$ indicating a
slower response for the left arm. Correlation of both arms was at a low of -0.11 indicating that such increase in reaction time is not systematic. Most subjects with an Affected Right Arm balanced in distribution around the line Y=X indicating similar reaction time with both arms. Correlation was 0.76 indicating more group consistency in reaction time for both arms as compared to subjects with an Affected Left Arm.

Finally in Figure 6.8D when comparing reaction time for both arms during Shoulder Extension, most subjects with an Affected Left Arm (seven of ten) were above the line Y=X indicating a longer reaction time for their impaired left arm than their right arm. Again, correlation was at a low of -0.18 indicating a non systematic increase in reaction time for the left arm. Four of ten subjects with an Affected Right Arm fell below the line Y=X indicating a longer reaction time for their right arm as compared to their left arm while most other subjects fell very close to the line Y=X. Correlation was at a high of 0.8 indicating a high group consistency in reaction time between both arms.

**Discussion and Frame Selection:**

First it is important to note that a higher group correlation was found for control subjects when analyzing reaction time through the Spatial Frame as compared to the Muscular Frame. The higher group consistency was therefore appealing for the choice of the Spatial Frame as our benchmark for analysis of reaction time.

As well, two previous studies analyzing reaction time of stroke patients to a visual stimulus [43, 44] both reported that stroke subjects seemed to present a longer reaction time when a visual stimulus was presented on the side contra-lateral to the lesion location. Analysis of reaction time through our Spatial Frame showed results that were
mostly similar to both of these studies as some subjects with an Affected Left Arm (Right Hemisphere lesion) presented longer reaction time for movements to the left with both arms (data points above line Y=X). Some subjects with an Affected Right Arm (Left Hemisphere lesion) also presented slightly longer reaction times for movements to the right mainly with their right arm.

6.2.2 New Analysis of First Peak Velocity

In this subsecion we present the analysis of first peak velocity using the Spatial Frame and the Muscular Frame.

6.2.2.1 Spatial Frame:

Figure 6.9A presents a comparison of first peak velocity (fpvel) for movements to the left with the left and right arm. In Section 5 (Figure 5.4) we noted a range in fpvel for control subjects that are also present in Figure 6.9A. Many control subjects lie close to the line Y=X therefore indicating similarity in fpvel for movements to the left with both arms. The correlation value was 0.68 indicating some inconsistencies in fpvel for both arms. Note that one control subject presented a much higher fpvel with their left arm than their right arm (data point above the line Y=X) and some subjects presented a higher fpvel with their right arm as compared to their left arm (data points below the line Y=X).
Figure 6.9 Analysis of first peak velocity with the Spatial Frame. First row plots (A and B) represent a comparison of each spatial movement between both arms. Second row plots (C and D) represent a comparison between both spatial movements of each arm. Rc, Rr and Rl represent correlation values for the control group, subjects with an Affected Right Arm and subjects with an Affected Left Arm respectively. Note that each diagonal line represents the line Y=X.

In Figure 6.9A four of nine subjects with an Affected Left Arm were slightly below the line Y=X indicating a higher \( f_{pvel} \) for movements to the left with their right arm as compared to their left arm. As well, these subjects fell below the control cluster indicating a lower \( f_{pvel} \) for both arms than control subjects. These results also agree with our previous findings from Table 5.3 (See Section 5) where the average \( f_{pvel} \) for each
arm of subjects with an Affected Left Arm was lower than that of the control average. Correlation was 0.67 indicating some group inconsistencies in \(fpvel\) for both arms. Note that one subject with an Affected Left Arm paradoxically presented a higher \(fpvel\) for their left arm as compared to their right arm (point above the line \(Y=X\)). Subjects with an Affected Right Arm presented a high correlation of 0.93 indicating high group consistency in \(fpvel\) for movement to the left with both arms. Seven of ten subjects with an Affected Right Arm were slightly above the line \(Y=X\) indicating a higher \(fpvel\) for their left arm as compared to their right arm whereas three subjects presented a slightly higher \(fpvel\) for their right arm. One subject with an Affected Right Arm fell above the control cluster indicating a paradoxically higher \(fpvel\) for both arms than control subjects.

Figure 6.9B depicts a similar analysis to that of Figure 6.9A for movements to the right. Some control subjects are slightly away from the line \(Y=X\) indicating some differences in \(fpvel\) for the right arm and the left arm. Correlation for controls was at a high of 0.88 indicating group consistency in \(fpvel\) for movements to the right with the left and right arm. Some subjects with an Affected Left Arm are slightly above the line \(Y=X\) indicating a higher \(fpvel\) for their left arm and some are slightly below the line indicating a higher \(fpvel\) for their right arm. The correlation for subjects with an Affected Left Arm was at 0.66 indicating less consistency in \(fpvel\) for both arms than that of control subjects. Subjects with an Affected Right Arm were also distributed above and below the line \(Y=X\) and correlation was at 0.86 indicating a higher group consistency in \(fpvel\) than that of subjects with an Affected Left Arm.

Similar to results for reaction time in Figure 6.6, a higher group correlation (\(R=0.82\) and \(R=0.93\)) was found for control subjects in Figures 6.9C and 6.9D. In these
figures our analyses were reversed and we compared $fpvel$ for movements to the left and right of each individual arm as opposed to comparing the $fpvel$ of both arms for a given movement. In other words a higher consistency in $fpvel$ for control subjects is attained when comparing both movement directions for an individual arm as opposed to contrasting the behavior of both arms for a given movement. Note that most control subjects in Figures 6.9C and 6.9D also show high similarity in $fpvel$ for both movement directions of each individual arm. This is evident as most data points for control subjects lie very close to the line $Y=X$.

In Figure 6.9C four of nine subjects with an Affected Left Arm lie below the control cluster indicating a lower $fpvel$ for both movements with the left arm as compared to control subjects. Correlation was at a high of 0.94 indicating consistency in $fpvel$ for both movement directions. Note that one subject with an Affected Left Arm presented a higher $fpvel$ for movement to the left as compared to movement to the right. Nine of ten subjects with an Affected Right Arm lie very close to the line $Y=X$ indicating a high similarity in $fpvel$ for both movements with their left arm. Correlation was at a high of 0.98 indicating a high group consistency in $fpvel$ for both movement directions with the left arm. One subject with an Affected Right Arm presented a slightly higher $fpvel$ for movement to the left as compared to movement to the right. As well, the subject was slightly above the control cluster indicating a higher $fpvel$ than control subjects.

In Figure 6.9D subjects with an Affected Left Arm presented a high correlation of 0.88 indicating consistency in $fpvel$ for both movement directions with their right arm. Similarity was also observed as many subjects were close to the line $Y=X$. Subjects with an Affected Right Arm also showed a high correlation of 0.98 indicating a high
consistency in both movements with their right arm. Similarity in \( fpvel \) for both movement directions is also observed as most data points lie close to the line \( Y=X \).

### 6.2.2.2 Muscular Frame:

![Graphs of first peak velocity with the Muscular Frame.](image)

**Figure 6.10** Analysis of first peak velocity with the Muscular Frame. Left column plots (A and C) represent a comparison of movements around the elbow for both arms and right column plots (B and D) represent a comparison of movements around the shoulder for both arms. \( Rc, Rr \) and \( Rl \) represent correlation values for the control group, subjects with an Affected Right Arm and subjects with an Affected Left Arm respectively. Note that each diagonal line represents the line \( Y=X \).
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Figures 6.10A, 6.11B, 6.12C and 6.13D depict a comparison of first peak velocity (fpvel) for the left and right arm for each of four dominant muscle groups (Elbow Extension, Shoulder Flexion, Elbow Flexion and Shoulder Extension respectively). Control subjects show most similarity in fpvel for both arms only around Shoulder Flexion as many data points lie close to the line Y=X. Less similarity is observed for the other muscle groups. Correlation for controls was also high (R=>0.8) for most muscle groups (Figures 6.10A, 6.10B and 6.10C) indicating consistency in fpvel for both arms except for Shoulder Extension (Figure 6.10D) where correlation was at 0.67 indicating a lower consistency than the other muscle groups.

In Figure 6.10A, six of nine subjects with an Affected Left Arm lie below the control cluster indicating a lower fpvel for both arms during Elbow Extension than controls (See Table 5.3 in Section 5). Some subjects fell above, below and close to the line Y=X, indicating no general group similarity or bias in fpvel for both arms. Correlation of subjects with an Affected Left Arm was at 0.76 indicating group consistency in fpvel during Elbow Extension for both arms. Subjects with an Affected Right Arm also did not show a bias or similarity in fpvel for the left and right arm during Elbow Extension as some subjects fell above, below and close to the line Y=X. Correlation was at 0.79 indicating group consistency in fpvel for both arms during Elbow Extension. One subject with an Affected Right Arm paradoxically presented higher fpvel than most control subjects for both arm.

When analyzing Shoulder Flexion in Figure 6.10B we note that one subject with an Affected Left Arm presented a higher fpvel value for the left arm as opposed to the right arm while most other subjects were close to the line Y=X. This anomaly could be
the likely cause for the inconsistency in $fpvel$ for both arms inferred by the low correlation value (R=0.34). Most subjects (eight of ten) with an Affected Right Arm presented high similarity in $fpvel$ for both arms during Shoulder Flexion as most data points lie very close to the line Y=X. Correlation was at a high of 0.95 indicating a high group consistency in $fpvel$ for both arms.

Figure 6.10C depicts the $fpvel$ values during Elbow Flexion. Here we note that most (seven of nine) subjects with an Affected Left Arm were below the control cluster indicating a lower $fpvel$ during Elbow Flexion for both arms than control subjects. Interestingly one subject with an Affected Left Arm presented a zero value for median $fpvel$ of the left arm implying that no reaching attempt was made for any of the eight trials performed. Correlation for subjects with an Affected Left Arm was at a low of 0.13 indicating a low group consistency in $fpvel$ for both arms during Elbow Flexion. Subjects with an Affected Right Arm did not show bias in $fpvel$ for either arms as some points fell below and some above the line Y=X. As well, few subjects were close to the line Y=X indicating less similarity in $fpvel$ for both arms during Elbow Flexion. Correlation was found to be at a high of 0.85 indicating group consistency in $fpvel$ for both arms.

Most subjects (seven of nine) with an Affected Left Arm presented high similarity in $fpvel$ for both arms during Shoulder Extension (Figure 6.10D) as shown by data points close to the line Y=X. One subject presented a higher $fpvel$ for the left arm as compared to the right arm. Correlation was at a high of 0.75 indicating group consistency in $fpvel$ for both arms during Shoulder Extension. Subjects with an Affected Right Arm showed some similarity in $fpvel$ for both arms during Shoulder Extension. Correlation of the group was at a high of 0.81 indicating consistency for both arms.
Discussion and Frame Selection:

It is expected that if a stroke subject suffers impairment for a given arm, they would present a different \( fpvel \) than that of the non-impaired arm. Inconsistencies in \( fpvel \) between both arms for stroke subjects are therefore expected. Our analysis of the Spatial Frame imply much higher correlations for subjects with an Affected Right Arm and subjects with an Affected Left Arm than that of the Muscular Frame (See Figures 6.9 and 6.10). The Muscular Frame is therefore the more favorable framework of analysis for \( fpvel \) as it captures more inconsistencies between both arms that are more likely present due to stroke.

6.2.3 Standard Deviation Analysis

In this subsection we present an analysis of standard deviation for the selected frame of each parameter. Standard deviation is presented to show noise that led to the selection of the median for our previous analysis as compared to the mean.

6.2.3.1 Standard Deviation Analysis for Reaction Time

Figure 6.11A depicts a comparison in average standard deviation of \textit{reaction time} for movements to the left with the left and right arm (calculated over all trials for all three targets). Control subjects show a low correlation of 0.48 indicating a low consistency in standard deviation between their left and right arm for movements to the left. Low similarity in standard deviation for both arms was observed as many control subjects fell at a distance above and below the line \( Y=X \).
Figure 6.11 Standard deviation analysis of reaction time. Top row plots (A and B) represent a comparison of each spatial movement between both arms. The bottom row plots (C and D) represent a comparison between both spatial movements of each arm. \( R_c \), \( R_r \) and \( R_l \) represent the correlation for the control group, subjects with an Affected Right Arm and subjects with an Affected Left Arm respectively. Note that each diagonal line represents the line \( Y=X \).

One subject with an Affected Right Arm presented a higher standard deviation for their left arm as compared to their right arm (data point above the line \( Y=X \)) while all other subjects with an Affected Right Arm showed similar standard deviation for both arms (data points close to the line \( Y=X \)). The correlation for subjects with an Affected Right Arm was at 0.46 indicating inconsistencies in standard deviation in reaction time for movements to the left with both arms. It is interesting to note that all subjects with an
Affected Left Arm presented a higher standard deviation in reaction time for movements to the left with the left arm as compared to the right arm. Correlation was at a high of 0.85 indicating a systematic increase in standard deviation for the left arm.

When analyzing movements to the right (6.11B), control subjects presented less similarity in standard deviation for the left and right arm. Correlation was also at a low of 0.27 indicating a high inconsistency in standard deviation for both arms. All but one subject with an Affected Right Arm presented a higher standard deviation for their right arm (nine of ten data points below line Y=X). Correlation was at 0.45 indicating that such increase in standard deviation was not systematic. Five of nine subjects with an Affected Left Arm presented a higher standard deviation for their left arm whereas two subjects presented a higher standard deviation for their right arm. Correlation was at 0.38 indicating inconsistency in standard deviation for the left and right arm.

Similar to results from Figure 6.7, a higher correlation was found for control subjects when we reversed our analysis and compared standard deviation of reaction time between both movement directions for an individual arm. Correlation for the right arm however (R=0.93), was found to be higher than that for the left arm (R=0.78). More similarity between movements to the left and movements to the right was also visible for the right arm as compared to the left arm (more data points close to line Y=X).

Figure 6.11C illustrates the standard deviation in reaction time for movements to the left and movements to the right with the left arm. Subjects with an Affected Right Arm presented no bias in standard deviation for a given movement. Correlation was at 0.79 indicating consistency in standard deviation for both movements. All subjects with
an Affected Left Arm presented a higher standard deviation for movements to the left as compared to movements to the right. Such increase in standard deviation could be systematic as the group correlation for subjects with an Affected Left Arm was found to be at a high of 0.85.

When analyzing the right arm in Figure 6.11D, five of ten subjects with an Affected Right Arm presented a higher standard deviation for movements to the right as compared to movements to the left. Correlation was found to be at 0.75 indicating consistency in standard deviation for both movements. Three of nine subjects with an Affected Left Arm presented a higher standard deviation in reaction time for movements to the right while only one subject presented a higher standard deviation for movements to the left. All other subjects presented similar standard deviation for both movements. Correlation was at a low of 0.38 indicating a low group consistency in standard deviation for both movements with the right arm.

Discussion:

Analysis of standard deviation for reaction time indicate that some control subjects present inconsistent and high reaction time for some movements with either the left or right arm (See Figure 6.11A-D). Since standard deviation is calculated over the mean of eight trials, the likely explanation for the behavior of some control subjects could be attributed to inattention during one or few trials. This has been previously observed in our new reaching diagrams (See Section 6.1) and was suggested to be likely caused by lack of motivation or due to the lengthy process involved in task completion. Analysis of stroke subjects however, revealed some interesting observations. For subjects with an Affected Left Arm (Right Hemisphere lesion), standard deviation was higher for
movements to the left with their left arm as compared to their right arm as well standard deviation was higher for movements to the left with their left arm as compared to movements to the right with the same arm (See Figure 6.11A and 6.11C). A high correlation observed for these subjects suggest that such increase in standard deviation is likely systematic. Subjects with an Affected Right Arm (Left Hemisphere lesion) presented a higher standard deviation for movements to the right as compared to movements to the left with their right arm (See Figure 6.11D). Correlation was also high indicating consistency for most subjects. The observed increase in standard deviation for specific movement directions that are contral-lateral to the lesion location once again indicates that analysis of reaction time through the Spatial Frame is in agreement with previous studies [43, 44].

6.2.3.2 Standard Deviation Analysis for First Peak Velocity

Figures 6.12 A, B, C and D present a comparison of standard deviation in first peak velocity ($fpvel$) between both arms for four dominant muscle movements (Elbow Extension, Shoulder Flexion, Elbow Flexion and Shoulder Extension respectively). Many control subjects are observed to have a higher standard deviation for the left arm as compared to the right arm across all four dominant muscle groups. The highest correlation found was at 0.50 (Elbow Flexion Figure 6.12C) indicating that such increase in standard deviation for the left arm is not systematic.
Figure 6.12 Standard deviation analysis of first peak velocity. Left column plots (A and C) represent a comparison of first peak velocity for movements around the elbow with both arms. The right column plots (B and D) represent a comparison of first peak velocity for movements around the shoulder with both arms. Rc, Rr and Rl represent the correlation for the control group, subjects with an Affected Right Arm and subjects with an Affected Left Arm respectively. Note that each diagonal line represents the line Y=X.

When analyzing Elbow Extension (Figure 6.12A) eight of ten subjects with an Affected Right Arm and seven of nine subjects with an Affected Left Arm presented a higher standard deviation for their left arm as compared to their right arm (points above line Y=X). Correlation for both groups was at 0.62 indicating some inconsistency in this systematic increase in standard deviation for the left arm. A lower correlation was found
for both groups (R=0.20 and R=0.04) when analyzing standard deviation in $fpvel$ for Shoulder Flexion (Figure 6.12B). Six of nine subjects with an Affected Left Arm presented a higher standard deviation for their left arm as compared to their right arm and no bias was observed for subjects with an Affected Right Arm.

Figure 6.12C presents standard deviation in $fpvel$ for both arms during Elbow Flexion. Subjects with an Affected Left Arm and subjects with an Affected Right arm both presented low correlations (-0.04 and -0.08) indicating high inconsistency in standard deviation for both arms. As well, no general bias in standard deviation for either arms was found for both stroke groups. When analyzing Shoulder Extension (Figure 6.12D), subjects with an Affected Right Arm presented a correlation of 0.62 indicating some consistency in standard deviation for their left and right arm. Six of nine subjects with an Affected Left Arm presented a higher standard deviation for their left arm as compared to their right arm. Correlation was at a low of -0.15 indicating that such increase in standard deviation was not systematic.

**Discussion:**

More control subjects were observed to present a higher standard deviation for their left arm as compared to their right arm across all dominant muscle groups. However, correlation was low indicating that such increase is not systematic. A likely explanation for this observation could be that more control subjects were right handed and therefore use their right arm more regularly in daily tasks. The initial velocity of movement for the right arm could therefore be less variable across all trials for the right arm as compared to the left arm resulting in lower standard deviation.
Some subjects with an Affected Left Arm presented a slightly higher standard deviation for their left arm as compared to control subjects across all muscle groups. However, no dramatic differences between control and stroke subjects were observed implying that variability in initial velocity for our reaching task might not be strongly influenced by the presence of stroke.

### 6.3 Correlation of Summarized Parameters with Clinical Scores

In this subsection we correlate the newly summarized parameter values for reaction time and $f_{pvel}$ with the Purdue Pegboard score and the Chedoke McMaster Score. Note that clinical scores were not available for all of our stroke subjects.

#### 6.3.1 Reaction time vs Purdue Pegboard

Figure 6.13 depicts the correlation of reaction time for each movement of each arm with the corresponding Purdue hand score. Correlation for the left arm (Figures 6.13A and 6.13C) was found to be higher than correlation for the right arm (Figures 6.13B and 6.13D). Our interest however, relates to detecting stroke subjects who fall above the control range (reaction time higher than two control standard deviation units). This will therefore indicate an impairment that manifests as a delayed response.
Figure 6.13 Correlation of reaction time with the Purdue Score for some stroke subjects. The blue line represents the average control value for the given movement of the selected arm. The black lines represent the distribution range for controls. +2CSTD represents the value at two standard deviation units above the control average. -2CSTD represents two standard deviation units below the control average. Left column plots (A and C) represent correlations for both movements of the Left Arm with the Purdue hand score and right column plots (B and D) represent correlations for both movements of the Right Arm with the Purdue hand score.

When moving to the right with the left arm (Figure 6.13A), four subjects with an Affected Left Arm presented reaction time values above the control range (higher than two control standard deviation units). Only one subject with an Affected Right Arm fell above the control range. When moving to the left with the left arm (Figure 6.13C) three subjects with an Affected Left Arm fell above the control range and no subjects with an Affected Right Arm fell above the control range.
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For movements to the right with the right arm (Figure 6.13B) only one subject with an Affected Right Arm fell above the control range while all other stroke subjects fell within the normal control range. For movements to the left with the right arm (Figure 6.13D), no stroke subjects were noted to fall above the control range.

Although results in Figure 6.13 were not always similar for both movement directions of a given arm, it is important to note that some stroke subjects with a low Purdue hand score for a given arm did not present impairment in reaction time as they fell within the control range. Also, one subject with an Affected Right Arm who presented a high Purdue score fell above the control range for movements to the right with the right arm. This suggests that a hand dexterity impairment captured through the Purdue Pegboard test does not necessarily imply impairment in response to stimulus as seen through longer than normal (control range) reaction time. Furthermore, we note that many stroke subjects fell in the control range when analyzing the arm affected by stroke. This therefore indicates that our new analysis frame (Spatial Frame) still presents a challenge at separating control and stroke subjects when analyzing each movement for each arm separately.
6.3.2 Reaction time vs Chedoke McMaster

Figure 6.14 Correlation of reaction time with the Chedoke Score for some stroke subjects. The blue line represents the average control value for the given movement of the selected arm. The black lines represent the distribution range for controls. +2CSTD represents the value at two standard deviation units above the control average. -2CSTD represents two standard deviation units below the control average. Left column plots (A and C) represent correlations for both movements of the Left Arm with the Purdue hand score and right column plots (B and D) represent correlations for both movements of the Right Arm with the Purdue hand score.

Figure 6.14 presents a similar correlation framework to that of Figure 6.13 except correlation is calculated with the Chedoke arm score instead of the Purdue hand score. Similar to the results in Figure 6.13, correlation for the left arm was found to be higher than that for the right arm.
When moving to the right or to the left with the left arm (6.14A and 6.14C), three subjects with an Affected Left Arm fell above the control range (higher than two control standard deviation units). Only one subject with an Affected Right Arm fell above the control range for movements to the right with the left arm. When moving to the right with the right arm (Figure 6.14B), only one stroke subject with an Affected Right Arm fell above the control range. No stroke subjects fell above the control range for movements to the left with the right arm (Figure 6.14D).

In general results from Figure 6.14 are similar to that of Figure 6.13 where some stroke subjects with a low Chedoke score fell within the control range and some subjects with a high Chedoke score fell above the control range. Analysis of each movement for each arm separately also shows the difficulty in separating control and stroke subjects.

### 6.3.3 First Peak Velocity vs Purdue Pegboard

$Fpvel$ for Elbow Extension and Elbow Flexion of each arm is plotted against the corresponding Purdue hand score (Figures 6.15A to 6.15D). The highest correlation ($R=0.76$) was found for Elbow Flexion of the left arm. Most stroke subjects fell within the control range for Elbow Extension and Elbow Flexion of both arms (See Figures 6.15A to D). Only two of six subjects with an Affected Left Arm fell below the control range at Elbow Flexion of the left arm (Figure 6.15C) indicating a slower initial movement.
Figure 6.15 *Correlation of first peak velocity with the Purdue Score for some stroke subjects.* The blue line represents the average control value for the given movement of the selected arm. The black lines represent the distribution range for controls. +2CSTD represents the value at two standard deviation units above the control average. -2CSTD represents two standard deviation units below the control average. Top row plots (A and B) present the correlation for Elbow Extension with the left and right arm respectively to the Purdue score. Bottom row plots (C and D) present the correlation for Elbow Flexion with the left and right arm respectively to the Purdue score.

Only one subject with an Affected Right Arm fell slightly below the control range through Elbow Extension of the right arm (See Figure 6.15B). Paradoxically one subject
with an Affected Right Arm fell above the control range for both muscle movements of each arm indicating a faster initial movement (See Figures 6.15A to D).

Significant correlation was only found with Elbow Flexion of the left arm. However, low correlations observed for Elbow Extension of the left arm and both muscle groups of the right arm indicate that a low Purdue score does not necessarily imply a slow initial movement (low \( fpvel \)). As well results from Figure 6.15 indicate even more difficulty in separating stroke patients then with reaction time (See Figures 6.13 and 6.14). The control range indicates variability in \( fpvel \) for each arm; this has been observed previously through our linear analysis across all target directions (See Section 5). This variability presents a challenge in separating control and stroke subjects as many stroke subjects fall in the range.

6.3.4 First Peak Velocity vs Chedoke McMaster score

\( fpvel \) for Elbow Extension and Elbow Flexion of each arm is plotted against the corresponding Chedoke Arm score (Figures 6.16A to 6.16D). The highest correlation (R=0.87) was found for Elbow Flexion of the left arm. Most stroke subjects fell within the control range for both muscle groups of each arm. Two subjects with an Affected Left
Figure 6.16 Correlation of first peak velocity with the Chedoke Score for some stroke subjects. The blue line represents the average control value for the given movement of the selected arm. The black lines represent the distribution range for controls. +2CSTD represents the value at two standard deviation units above the control average. -2CSTD represents two standard deviation units below the control average. Top row plots (A and B) present the correlation for Elbow Extension with the left and right arm respectively to the Purdue score. Bottom row plots (C and D) present the correlation for Elbow Flexion with the left and right arm respectively to the Purdue score.

Arm fell below the control range in Figure 6.16C (Elbow Extension of the left arm) and one subject with an Affected Right Arm fell slightly below the control range in Figure 6.16B (Elbow Flexion of the right arm). Paradoxically one subject fell above the control range (faster initial movement) for both dominant muscle groups of each arm.
Results from Figure 6.16 are similar to that of Figure 6.15 as it is already known that most stroke subjects fell within the control range through analysis of $fpvel$. These results also support the general observation of less separation between control and stroke subjects through the analysis of an individual arm.

6.3.5 Summary of Correlation Analysis:

It is first important to note that only six of nine subjects with an Affected Left Arm and seven of ten subjects with an Affected Right Arm had recorded clinical scores. It is therefore difficult to generalize our results to our entire stroke group.

Although reaction time and $fpvel$ have shown some correlation with clinical scores, we have demonstrated through our correlation analysis that a long reaction time or a slow initial movement (low $fpvel$) does not necessarily imply a low clinical score (Purdue or Chedoke). We therefore affirm that both parameters should not be used as substitutes and rather as complimentary tools to the current existing clinical tools (Chedoke McMaster and Purdue Pegboard).

6.3.6 Summary of New Analysis Framework:

So far we have shown that the Spatial Frame and the Muscular Frame could both be used in our analysis of reaction time and $fpvel$ respectively. In Section 5 we used quantitative analysis to show separation of control and stroke subjects through linear analysis of each arm. Although more separation was visible when comparing data for both arms through our new analysis framework, we were still interested in applying a
clustering technique to test the potential of our new framework for clustering each group separately. In the following subsection we hierarchical clustering to test the separation of control and stroke subjects through the use of data from both arms as opposed to data from a single arm.

6.4 Application of Hierarchical Clustering

The main goal of applying Hierarchical Clustering was to test the power of the newly summarized framework data for reaction time and fpvel at grouping control subjects separately from stroke subjects.

The Euclidean Distance was calculated on the value of the attributes of the frame that was selected for a given parameter. For reaction time we used the summarized attributes of the Spatial Frame (Median reaction time for Left Movement of each arm and Median reaction time for Right Movement of each arm). For fpvel two select attributes from the Muscular Frame were used (Elbow Extension and Elbow Flexion). This was done as we observed in our results slight segregation of controls from stroke subjects around the elbow more than the shoulder. (See Figure 6.10).

The average linkage method was used in the clustering algorithm (See Section 5.1.). With this method we expect that control subjects would group together and that stroke subjects would group separately based on the affected arm (See Figures 6.17 and 6.18). Ideally we expected three clusters for each of our subject groups (control, Affected Right Arm and Affected Left Arm) we thus used the automated cluster selection algorithm to
select three clusters from the dendrogram (See Section 4.4.3). However, from our previous analysis we expect that some stroke subjects (especially subjects with an Affected Right Arm) might fall within the control cluster. A silhouette plot for the three clusters was then generated. A negative silhouette score for given point in a chosen cluster implies that on average the point is more similar to other points in other clusters as compared to points in its own cluster and vice versa.

### 6.4.1 Clustering on Reaction Time

Figure 6.17 depicts results of clustering on reaction time. The main cluster (Cluster 2 in the silhouette plot) contained most subjects. The silhouette values for Cluster 2 were mainly positive and a few negative values represented three subjects with an Affected Left Arm. The two other clusters each consisted of a single data point. Cluster 1 corresponds to a control subject and Cluster 3 corresponds to a subject with an Affected Left Arm. Both subjects presented a long reaction time for movements to the left with the right arm (See Figure 6.7).
Heirarchial Clustering on Summarized Spatial Attributes of Reaction Time

C-Control
AR-Affected Right Arm
AL-Affected Left Arm

![Dendrogram and Silhouette Plot](image)

**Figure 6.17** Dendrogram and Silhouette Plot generated through clustering with reaction time using the Spatial Frame attributes. The horizontal line in the dendrogram crosses three vertical lines that are chosen as cluster points for the silhouette plot.

Four subjects with an Affected Right arm grouped together in the same sub-cluster in Cluster 2. Those subjects presented a long *reaction time* for movements to the right with the right arm.
6.4.2 Clustering on First Peak Velocity

Figure 6.18 Dendrogram and Silhouette Plot generated through clustering with \( fpvel \) using the Elbow Extension and Elbow Flexion attributes. The horizontal line in the dendrogram crosses three vertical lines that are chosen as cluster points for the silhouette plot.

Four control subjects clustered separately (Cluster 2) from all other controls as they presented a high value of \( fpvel \) for Elbow Extension and Elbow Flexion. Six subjects with an Affected Left arm grouped together as a sub-cluster in Cluster 3. This was mainly as a result of the low value of \( fpvel \) observed for those subjects (See Figure 7.10). Many silhouette values were negative indicating that many cluster points showed more similarity to points in other clusters.
6.4.3 Summary of Hierarchical Clustering:

For reaction time and fpvel, hierarchical clustering seemed to group some stroke subjects away from control subjects. It was also common to observe stroke subjects with the same affected arm grouping together with proximity in the same sub-cluster. These results suggest that data from both arms is indeed useful at grouping together stroke subjects based on their affected arm. Therefore, any design of a clinical scoring system should incorporate data from both arms rather than from a single arm.

6.5 Summary of Results

Reaction Time:

Through the analysis of reaction time an important observation was recorded. Although control subjects show variability in magnitude of reaction time, they tend to show symmetry in reaction time value for both arms and both movement directions. Although some stroke subjects show a longer reaction time than control subjects, a stronger observation yielded in our results is that of the difference in reaction time for both arms caused by single arm impairments. Symmetry in reaction time for both arms and both movement directions could therefore be incorporated as part of a new clinical score on reaction time.

First Peak Velocity:

Analysis of fpvel for different muscle groups proved more difficult as symmetry of both arms for control subjects was only observed on Shoulder Extension and Shoulder
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Flexion. Many stroke subjects also showed similarity in $fpvel$ for the Shoulder muscle groups. For Elbow Extension and Elbow Flexion the only notable difference between control and stroke subjects was that of magnitude as some stroke subjects (Affected Left Arm) presented a lower value for $fpvel$. 

Chapter 7

New Clinical Scheme on Reaction Time

In this chapter we present a new scoring system that incorporates the reaction time parameter. Details of score calculation as well as observations that have led to the formulation our scoring system are also discussed.

7.1 Review of Reaction Time

Based on our results from Section 6 we have identified for the reaction time parameter spatial attributes that show impairments manifesting as delayed response to certain movement directions. The median reaction time value for Targets 315, 0 and 45 degrees were averaged and labeled as Right Movement and the median value for Targets 135, 170 and 215 degrees were averaged and labeled as Left Movement. Given these two attributes for each arm, there are two ways of analyzing our data:

1) Comparing reaction time to a certain movement direction between both arms (e.g. Left Movement of left arm and Left Movement of right arm).

2) Comparing reaction time between both movement directions for an individual arm (e.g. Left Movement of left arm and Right Movement of left arm).
7.2 Observation for Control Subjects

From Section 6 we concluded that data points for most control subjects lie almost symmetrical along the line Y=X for the four different plots used in the Spatial Frame (See Figure 6.7). The observation for control subjects is thus summarized as follows (See Figure 7.1)

1) Controls show similar reaction time when moving with either arm to the same movement direction.

2) Controls show similar reaction time when moving with the same arm to either movement directions.

7.3 Establishment of Normative Scores

We assume that our observations for control subjects represent the normal behavior of reaction time. We therefore design two normative scores based on data for our control subjects.

a) Magnitude Score: To calculate the Magnitude Score we first determine the average and standard deviation value of median reaction time for all control subjects. The Magnitude Score for any given subject is then calculated as follows:

\[ \text{Magnitude Score for a given subject} = \frac{\text{Given median value} - \text{Average median control value}}{\text{Standard deviation of average control value}} \]
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Figure 7.1 Two observations for reaction time of control subjects.

The difference between a subject value and the control average is divided by the standard deviation in order to normalize to the standard deviation of controls. It is therefore expected that the Magnitude Score for most control subjects will be close to zero. A positive value will indicate a median value higher than the average median control value and hence a longer reaction time and vice versa (See Figure 7.2). For both observations in Figure 7.2, the Magnitude Score need only be calculated for each movement of each arm once.
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Median reaction time for a given movement

![Median reaction time for a given movement diagram](image)

Observation 1

Median reaction time for a given arm

![Median reaction time for a given arm diagram](image)

Observation 2

Figure 7.2 Clinical Scheme based on observations for control subjects.
b) Asymmetry Score

The Asymmetry Score is concerned with the deviation of a subject from the normal observation of similar *reaction time* between both arms and/or both movement directions. First, the average and standard deviation of the absolute perpendicular distance from the line Y=X for all control subjects is calculated. The absolute distance was used as we observed a balanced distribution of control subjects around the line Y=X. The asymmetry of any given subject is then calculated as the perpendicular distance between the point and the line Y=X. A positive or negative distance will then indicate the slower side (Right or Left). For the purpose of our calculations we selected right as positive and left as negative (See Figure 7.2). The Asymmetry Score for any given subject is then calculated as follows:

\[
\text{Asymmetry Score for a given subject} = \frac{\text{Given distance value} - \text{Average control distance value}}{\text{Standard deviation of average control distance value}}
\]

Once again, the difference is normalized using the standard deviation value of control subjects. The Asymmetry Score is then calculated for each movement separately (difference between both arms) and for each arm separately (difference between both movements).
7.4 Results of Scheme Calculation

In this subsection we present the Magnitude and Asymmetry scores for all of our control and stroke subjects. We also provide some brief analysis on discuss our results.

7.4.1 Magnitude Score

The Magnitude Scores (control standard deviation units) for the left and right arm are shown in Figures 7.3 and 7.4 respectively. In both figures, the scores for each subject group are shown by means of a histogram. As well, movements to the left are shown by histogram plots on the left column and movements to the right are shown by histogram plots on the right column. Recall that a positive score implies a longer than control average reaction time and vice versa. When analyzing both movements with the left arm in Figure 7.3, it can be noted that most control subjects (blue histogram) fell within the range of -2 to +2 standard deviation units. Only one control subject presented a score of +3 standard deviation units for movements to the left with the left arm. As well, frequency was observed to be high for lower scores indicating that many control subjects are close to the control average. Subjects with an Affected Right Arm (red histogram) also fell within the same control range (-2 to +2) implying that reaction time for movements with their left arm was close in magnitude to that of control subjects.

Six of nine subjects with an Affected Left Arm (green histogram) fell above two standard deviation units for movements to the left and five subjects fell above two standard deviation units for movements to the right. These scores indicate longer reaction time for movements with the left arm as compared to control subjects.
When analyzing movements with the right arm (Figure 7.4) most control subjects fell within the range of +2 to -2 standard deviation units (SDU). One subject however presented a score of +4 SDU for movements to the left and +3.5 SDU for movements to the right.
Figure 7.4 Magnitude Scores for both movements with the right arm of all subjects. Scores for movement to the left are shown on the left column plots and scores for movement to the right are shown in the right column plots. Positive scores imply longer reaction time and negative scores imply shorter reaction time than the control average.

Three of ten subjects with an Affected Right Arm fell slightly above 2 SDU for movements to the right while no subjects fell off the control range for movements to the left. This therefore implies that for these three subjects reaction time was longer for movements to the right as compared control subjects. Most subjects with an Affected Left Arm fell within the same control range (+2 to -2 SDU) for both movements. However,
one subject presented a Magnitude Score of +4.5 SDU for movements to the left and +3 SDU for movements to the right.

7.4.2 Asymmetry Score

The Asymmetry Score was calculated for both observations mentioned earlier (See Figure 7.2). Results for Observation 1 are displayed in Figure 7.5 and results for Observation 2 are displayed in Figure 7.6. Asymmetry scores for all subject groups are represented by histograms.

In Figure 7.6 the Asymmetry Score for movements with both arms to the same spatial direction is presented. Thirty of thirty three control subjects fell within the range of +1 to -1 SDU indicating similarity in reaction time between both arms for both movements. Sub observation is unexpected as data points should lay within the range of two standard deviation units. The likely explanation could be due to outliers. One control subject fell at approximately +4 SDU for both movements indicating a longer reaction time with their right arm as compared to their left arm.

When analyzing movements to the left, only two subjects with an Affected Right Arm fell out of the expected normative range (+2 to -2). One subject presented a score of -3.5 SDU indicating a longer reaction time with their left arm while another subject presented a score of +3 SDU indicating a longer reaction time with their right arm. Four subjects with an Affected Left Arm presented scores of -3 SDU and below indicating a longer reaction time for the left arm while one subjects presented a score of +3 and above indicating a longer reaction time with the right arm.
Figure 7.5 Asymmetry Scores for Observation 1. Asymmetry Scores for movements to the left with both arms is shown in the left column plots and Asymmetry Scores for movements to the right with both arms is shown in the right column plots. A positive score implies a longer reaction time for movements with the right arm as compared to the left arm and vice versa.

When analyzing scores for movements to the right, one subject with an Affected Right Arm is noted to present an Asymmetry Score of +3.5 SDU which falls out of the control range. Five of nine subjects with an Affected Left Arm presented scores of -3 SDU and below indicating a longer reaction time with their left arm as compared to their right arm. One subject presented a score of +7 SDU indicating a longer reaction time with their right arm as compared to their left arm.
Figure 7.6 Asymmetry Scores for Observation 2. Asymmetry Scores for both movements with the left arm is shown in the left column plots and Asymmetry Scores for both movements with the right arm is shown in the right column plots. A positive score implies a longer reaction time for movements to the right as compared to movements to the left and vice versa.

Figure 7.6 depicts the Asymmetry Score for movements to the right and left with each individual arm. For most control subjects the distance from the line Y=X (similarity in reaction time for both movements) presented a narrow distribution around 0 SDU. For movements with the left arm however, three control subjects fell below -2 SDU indicating a longer reaction time for movements to the left as compared to movements to the right. For movements with the right arm, only one control subject fell below -2 SDU.
Two of ten subjects with an Affected Right Arm fell off the control range for movements with the left arm and five subjects fell off the control range for movements with the right arm. Six of nine subjects with an Affected Left Arm presented Asymmetry Scores out of the control range for movements with the left arm. On the other hand, four subjects fell out of the control range for movements with the right arm.

7.4.3 Discussion

First it is important to note that a few (two to three) control subjects presented Magnitude and Asymmetry scores that fell out of the general score distribution for control subjects. Indeed one of the subjects who presented a long reaction time as observed through the Magnitude Score has been reported in Section 6 to be slower than normal at following instructions and experimental protocols. As more control subjects are collected, it may be necessary in the future to examine these subjects (at 4 SDU or above) for any possible neurological disorders not identified through our screening process. If a valid argument is presented to nullify such subject as a control then such data point should be removed from the scheme calculation.

Higher Asymmetry Scores were observed for stroke subjects as compared to Magnitude Scores. A possible reason could be that standard deviation of control subjects for magnitude of reaction time was higher than the standard deviation of the similarity distance. Therefore normalizing to a higher standard deviation was the likely result of lower Magnitude Scores as compared to the Asymmetry Scores.

As well, more subjects with an Affected Right Arm fell out of the control range through the analysis of the Asymmetry Scores as compared to the Magnitude Scores.
CHAPTER 7. NEW CLINICAL SCHEME ON REACTION TIME

These results suggest that our Asymmetry Score is sensitive to slight differences in reaction time between both arms and/or both movement directions.

7.5 Summary

Our clinical scheme allows for comparing reaction time of stroke subjects directly to control subjects through the Magnitude Score. Although some stroke subjects are observed to fall well within the control range through the Magnitude Score, a slight difference in performance between both arms and/or both movement directions could still be captured through the Asymmetry Score. We predict that our clinical scheme will therefore be able to capture subtle impairments in reaction time that might manifest in movement symmetry rather than magnitude.
Chapter 8

Conclusion

In this Section we discuss the main accomplishments of our work using the bilateral limb KINARM device in studying reaching impairments due to stroke. We also examine possible limitations in our work and we offer suggestion for future research using the bilateral-arm KINARM device.

8.1 Main Accomplishments

In this subsection we note the main benefits of our work on the use of the dual arm KINAM device for the study of upper limb impairments due to stroke.

Flexibility in comparison to other research:

Contrasting our research to related work is essential in identifying differences or similarities in the reaching task or the stroke population that could be contributing to the observed differences or similarities in results.
The use of the bilateral KINARM device allows for easy comparison of reaching data for stroke subjects to other related work. In Section 5 we compared our results for reaction time and first peak velocity of the unaffected arm to other studies that analyzed the same parameters for the unaffected arm of a different stroke group involved in a different reaching task. The bilateral-arm device would also allow for contrasting results to other research that compares reaching performance of both arms as well as research that simply examines impairments in reaching of the affected arm.

**New visual tool assists in diagnosis:**

In Section 6 we presented a new visualization tool for completion of reaching trials. The tool offers clinicians the ability of quickly screening through all movement directions to identify specific impairments in reaching due to stroke. This would then assist in diagnosis of the impairment in reaching (spatial or muscular) and relating it to the lesion location in the brain.

**Categorization of parameters for reaching:**

We have shown in our work that when examining a given parameter calculated for the reaching task, two perspectives of quantifying deficits could be used to investigate the underlying impairments. The Spatial Frame relates to the impairment of visually detecting targets in specific spatial locations (right or left). The Muscular Impairment Frame relates to the impairment in reaching based on specific muscle group impairments. This is proposed in our thesis as a framework for analyzing any new parameter calculated for reaching (Example. total movement time).
CHAPTER 8. CONCLUSION

Correlation with other clinical assessment measures:

We have compared our results of reaction time and first peak velocity with the Chedoke Arm score and the Purdue Pegboard score. We have noted that although some correlation is observed, our parameters capture impairments (delayed response time) that are not captured by the clinical measures. Clinical measures however were also able to capture impairments not detected by our parameters. For example, the Purdue Pegboard score measures hand dexterity problems that our KINARM system is unable to capture. We therefore note that the KINARM system should not replace current assessment measures; rather its use could provide new additional information that could assist in rehabilitation.

New Clinical Scheme for Reaction Time:

Our detailed analysis of a single parameter (reaction time) calculated for the reaching task indicated very high symmetry in reaction time of control subjects when moving with either arms (left or right) and when moving to two different directions (left and right). This observation has led to the development of a clinical scheme that incorporated a normative asymmetry score for both arms. Although reaction time of some stroke subjects might fall well within the control range in terms of magnitude, they might show differences between movement directions with a single arm or differences between both arms for a single movement direction. Such differences are not detected with control subjects and therefore, the normative asymmetry score have shown potential being sensitive to such differences.
8.2 Current Limitations and Future Work

- Our stroke group mainly consisted of elderly subjects. Control subjects included in our study however contained a younger population and was not age-matched to the Stroke group. With more control data collected we suggest first the comparison of data for the younger and older control subjects. If major differences are observed then this suggests the need of only using age-matched control subjects in our study of reaching impairment due to stroke.

- Technicians have reported loss of focus during the reaching task of some subjects as a result of the lengthy process associated with the reaching task. Data outliers resulting from such inattention could reduce from the reliability of our data. We therefore recommend research into reducing the number of trials required for completion of the reaching task. The goal would be to determine the minimum number of trials that could be employed without major loss of information.

- When subjects do not complete all trials for many targets, the reaction time is set to a maximum value (1000 milliseconds) and the first peak velocity value is set to 0. It is therefore more difficult to analyze the reaching data for the given subject and identify the possible cause of impairment. We therefore suggest a future data filtering process to remove such subjects from our analysis yet provide clinicians with a low score indicating severe impairment in reaching.
The development of an automated movement offset algorithm is crucial to the study of many parameters such as total movement time and number of corrective movements. We hypothesize that these parameters would provide additional information on impairments that might not be captured by first peak velocity of reaction time. An automated movement offset technique will therefore allow for a more thorough investigation of all possible parameters calculated for the reaching task.

When more parameters are investigated and summarized using our Spatial Frame and Muscular Frame, we recommend the use of multi-dimensional visualization tools for clustering. Hierarchical clustering was used in our research and showed the potential of each parameter at separating control and stroke subjects. Future analysis should incorporate more than a single parameter to investigate their combined potential at separating out stroke subjects from control subjects.

As more subjects are collected, we recommend the application of advanced statistical tools such as t-test or ANOVA to examine the significance of our results or results from related future work on the KINARM.

Another task has been developed by Scott’s group and referred to as the Sensory Matching task. In this task a stroke subject’s vision is blocked and the robot moves the affected arm to a certain location on the horizontal space. The subject is then required to match such position with their unaffected arm. This task therefore can detect impairments in perception. There has been little analysis on
the data collected through the Sensory Matching task and we therefore strongly recommend such analysis in future work to investigate its assessment potential.

- A Case Base Reasoning system is currently being developed by Glasgow’s group at the School of Computing. The Case Based Reasoning system is being designed to assist rehabilitation therapists in assessment and treatment of a stroke patient by simply retrieving previous similar cases. The solution for such previous cases and their outcome (recovery or no improvement through rehabilitation) could be a helpful resource for therapists. A current challenge is to incorporate the KINARM data into the case base system along with other clinical measures. We therefore recommend research on summarizing parameter values or any of the normative scores developed and their proper incorporation into the Case Base system.

- Magnetic Resonance Imaging (MRI) has recently been used to retrieve an image of the brain for stroke patients and identify the specific lesion size and location caused by stroke. Such data should be summarized and properly incorporated in the clinical database. This data could be used to address issues due to specific lesions rather than assigning a general impairment category (Right Hemisphere Lesion or Left Hemisphere Lesion).
Bibliography


Appendix A

Data Extraction from the Clinical Database

For each subject (control or stroke) undergoing the clinical and the KINARM robotic assessment, all data recorded is stored in the Clinical Database in DB2. In this appendix we provide a brief review of the Clinical Database, we then discuss our methodology for data extraction needed to generate results in Section 6 and Section 7.

Clinical Database

Figure A.1 presents an overview of the database layout. When a subject is admitted to our study, basic information that is assumed to be invariant such as their subject code (name based), date of birth (DOB), weight and height are stored in the Subjects table. A unique key (SubjectKey) is then given to each subject.

A session in our study is defined as a block of robotic tasks (usually two) and clinical assessments that the subject needs to undergo. This block could be held over a single day or consecutive days usually depending on scheduling and experimental time capacity (health concerns for stroke patients). The Sessions table contains one or more session keys (with an associated date) for each unique SubjectKey. Stroke patients are usually invited back for assessment over time intervals to monitor recovery. However, in our study we were mainly interested in the first initial assessment session capturing impairments due to stroke at their earliest stage.
APPENDIX A

Clinical (Human2) Database Structure

Figure A.1 Layout of the Clinical Database.
In a single session a subject usually undergoes clinical assessments (including Purdue Pegboard and Chedoke McMaster) of upper limb impairments by a clinician, such data is then stored in the Assessments table. In each session a subject usually performs one or more sets with each arm (MainArm in the Sets table). Each set holds two tasks: the Sensory Matching Task (not reviewed in our thesis) and the Center-Out Reaching task (only task studied in our thesis). In a single session the subject might be required by the technician to perform more than a single set with each arm for inter-rater reliability testing. Data for each set is stored in the Sets table and a set can be uniquely identified with the SetKey.

The Center-Out Reaching task is discussed in detail in Section 4. The subject is required to reach to various peripheral targets from a center-hold position. Information detailing the exact location of each target is stored in the Conditions table. CondKey is the primary unique key stored for each target. Each subject is required to perform many repeat trials (generally eight) to each target. To identify the sequence (1st, 2nd, 3rd, etc.) of each trial, a unique key (TrialKey) is generated. Although the subject performs reaches with a single arm, data from both arms are usually recorded. The TrialArmID table therefore provides a way of selecting the arm of interest.

The Movement Onset algorithm developed by Scott and colleagues is applied to the hand velocity data to identify the movement onset point. Such information and other information detailing the inability to determine a valid onset point (no movement) is stored in the Features table and is used in our research to identify unsuccessful trials. Other useful information for a single trial such as the start time of the trial and time of target light illumination are stored in the Events table.
Finally, all other kinematic variables of interest (hand positions, velocities of the shoulder elbow and the hand, torques around the shoulder and elbow, EMG, etc.) are stored in the Derived_Signals table, the Signals table and the EMG table.

**Connecting to the Clinical Database within Matlab**

Matlab version R2007 was the tool used in our parameter visualization and analysis. To allow for direct access and querying of the database within Matlab, a software package in Java was developed by programmers at Scott’s lab [14]. The latest software package as well as instructions on how to connect to the database is available for research members at the following website:

http://limb.biomed.queensu.ca/members_only/database/database_clinical.htm

**Steps for Data Extraction**

- The database was first queried to retrieve the Sesskey of all subjects who performed the Center-Out reaching task (identified from the Sets table by TaskCode). Session keys for only the initial session of all subjects were retrieved.
- For each subject, the Sesskey is used to retrieve the Setkey of the reaching task for each arm. We then retrieve the target locations from the Conditions table.
- For each trial we determine, using data from the features table and the events table, the movement onset point and the peripheral target illumination time to calculate the reaction time for each trial. We also calculate the first peak velocity of the hand from the Derived_Signals table.
- The median and standard deviation values are computed and each stored in a different table.
APPENDIX A

- For each parameter (*reaction time* and *first peak velocity*), we now have four tables. Two tables hold the median and standard deviation values for all targets of the left arm and the two other tables hold the same information for the right arm. These tables were then used to generate many of our diagrams in Section 5 and Section 6.

- A similar process was used to determine the number of successful trials to each target. Such data was needed for our new visual tool in Section 6.1
Appendix B

Control Volunteer Screening Checklist

The following form is used by technicians at Scott’s lab to ensure that control volunteer subjects participating in the study on the KINARM system are free of musculoskeletal and neurological conditions.

Date Completed:__________

Completed By:________________________

Best Times for appointments:_______________________

Volunteer Contact Information:

Name:________________________________

Phone #:______________________________

Volunteer Script

Thank you for your interest in our study. We are currently conducting a study funded by the Canada Institute of Health Research through Queen’s University and St. Mary’s of the Lake Hospital. We are evaluating the use of robotic technology to assess the effects of Stroke on arm function. We are looking for volunteers over the age of 50 to act as our
control group. Participation will require about 4 hours of your time, divided over 2-3 sessions. If you are still interested I would like to ask you a few questions to determine if you are eligible to take part in our study.

Demographic

What is your age? _______

Male/Female (Circle One)

Neurological

Y  N

☐ ☐ Have you ever had a stroke? Mini-stroke or Transient Ischemic Attack (TIA)?

☐ ☐ Have you ever been diagnosed with a disease or condition affecting the brain or spinal cord (eg. Multiple Sclerosis, Parkinson’s disease, Huntington’s disease, Brain Aneurysm, Brain Tumor, Epilepsy)?

☐ ☐ Have you ever had a brain injury or closed head injury?

☐ ☐ Have you ever had brain surgery?

☐ ☐ Have you ever suffered a spinal cord injury?

☐ ☐ Have you ever had a radiculopathy or nerve root problem in the neck (cervical spine)?

☐ ☐ Have you ever had a brachial plexus injury (injury to a nerve in the shoulder(s)/arm(s))? 

☐ ☐ Have you ever had damage to a nerve in the arms (peripheral nerve injury) (Carpal Tunnel Syndrome would be allowable)?

☐ ☐ Have you ever been diagnosed with neuropathy/peripheral neuropathy/diabetic neuropathy?
APPENDIX B

Answering YES to any of the above questions excludes subjects from our study. These people should be thanked for their interest and time.

If answer is NO to the above questions then move on to next set below:

Musculoskeletal

Y  N

☐ ☐ Have you ever had a fracture to any of the bones of the shoulder, arm or wrist -
   including the collarbone (clavicle) or shoulder blade (scapula), the upper arm
   (humerus), the forearm (radius or ulna), the wrist (carpal bones)?

   Side (L/R/Both) and list bone(s)______________________________________________

☐ ☐ Do you have arthritis? What type (Osteo vs. Rheumatoid vs. other - circle)?

   What joint(s) are affected on what
   side?_____________________________________________________________________
   ________________________________________________________________________

☐ ☐ Have you ever dislocated your shoulder?

   Date___________ and Side (L/R/Both)

☐ ☐ Have you ever had a rotator cuff tear?

   Date___________ and Side (L/R/Both)

☐ ☐ Have you received therapy (eg. physical therapy, massage, chiropractic) for a
   shoulder problem in the last 3-4 months?

   (Y/N) If Yes – do you still have problem with the shoulder? Side (L/R)
Have you ever been diagnosed with a frozen shoulder (adhesive capsulitis)?

Date________ and Side (L/R/Both)

Have you ever received a corticosteroid injection for a shoulder problem?

Date________ and Side (L/R/Both)

Have you ever had surgery to your shoulders, arms, forearms, wrists or hands?

If Yes, Where was the surgery (eg. wrist)____________ and what was the purpose of the surgery (eg. Carpal Tunnel release)? ________________

Do you currently have tennis elbow/golfer’s elbow (medial or lateral epicondylitis)? Side (L/R/Both)

Do you have fibromyalgia or chronic pain affecting you neck, upper back or arms? Side (L/R/Both)

Answering YES to any of the above questions with a bilateral problem would exclude someone from the study. They should be thanked for their interest and time.

Most people who answer YES and have solely a unilateral problem may be used as controls for their “good” arm and the examiner should continue with the questionnaire. Ideal controls will answer NO to all questions and the examiner should continue with the questionnaire.

Congratulations, you qualify to be part of our study. As I’ve said before it involves about 4 hours of your time. There are three parts to the study which will require two visits.
APPENDIX B

Part number one is a clinical assessment performed by myself at St. Mary’s of the Lake. It takes between an hour and an hour and a half. In this part I’ll be asking some questions about your overall health, running you through some pencil and paper tests, as well as some tests of your vision and coordination. This will take about an hour.

Part number two is the robotic assessment. The robot we use is called the KINARM. For this assessment you will sit in a chair and your arms will be placed on top of and supported by the robot. You will be asked to perform movements or to let the robot move your arms for you. The whole process is not painful, nor is it invasive in anyway. The robotic assessment will take about one and a half hours and will take place at St. Mary’s of the Lake Hospital.

Part number three is the MRI assessment. The MRI is a large magnet that allows us to take a picture of your brain. You must be able to lay flat for approximately 1 hour in the MRI in order for it to take the required pictures. The MRI is located in the basement of Botterell Hall at Queen’s University. There are a number of screening questions that we need to complete to make sure you can do this portion of the study.

MRI Screening Checklist

<table>
<thead>
<tr>
<th>Y</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐ ☐ Have you had prior surgery or an operation of any kind? If <strong>YES</strong> Please Describe________________________________________________________________________</td>
<td></td>
</tr>
<tr>
<td>☐ ☐ Have you had an injury to the eye involving a metallic object (e.g. metallic slivers, foreign body)? If <strong>YES</strong> Please Describe________________________________________________________________________</td>
<td></td>
</tr>
</tbody>
</table>
| ☐ ☐ Have you ever been injured by a metallic object or foreign body (e.g. BB, bullet, shrapnel, etc.)? If **YES** Please
APPENDIX B

Describe__________________________________________________________
__________________________________________________________________

☐ ☐ Are you pregnant or suspect that you are pregnant?

☐ ☐ Do you have any history of claustrophobia, panic attacks, or seizures?

☐ ☐ Do you have any history of heart disease (angina, palpitations, heart attack, etc.)?

If YES Please
Describe__________________________________________________________
__________________________________________________________________

☐ ☐ Aneurysm clip(s)

☐ ☐ Neurostimulation system

☐ ☐ Cardiac pacemaker

☐ ☐ Spinal cord stimulator

☐ ☐ Implanted cardioverter defibrillator (ICD)

☐ ☐ Cochlear implant or implanted hearing aid

☐ ☐ Electronic implant or device

☐ ☐ Insulin or infusion pump

☐ ☐ Magnetically-activated implant or device

☐ ☐ Implanted drug infusion device

☐ ☐ Any type of prosthesis or implant? If YES Please

Describe__________________________________________________________
__________________________________________________________________
APPENDIX B

☐ ☐ Artificial or prosthetic limb

☐ ☐ Any external or internal metallic object (e.g. dentures, permanent retainer, IUD, metal sutures)?

☐ ☐ Any metallic fragment or foreign body?

☐ ☐ Medication patch (Nicotine, Nitroglycerine)?

☐ ☐ Hearing Aid? If YES will be asked to Remove before entering the magnet room

☐ ☐ Tissue expander (e.g. Breast)?

☐ ☐ Tattoo? If YES ask where the tattoo is?________________________________

☐ ☐ Body piercing? If YES ask where the piercing is/are and can they be removed for the study?

☐ ☐ Any Other implants? If YES please list:

________________________________________________________________________

☐ ☐ Can you lay flat for 45 minutes? (Y/N)
## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bi-lateral</strong></td>
<td>Both sides (right and left).</td>
</tr>
<tr>
<td><strong>Contra-lateral</strong></td>
<td>Opposite side.</td>
</tr>
<tr>
<td><strong>Distal</strong></td>
<td>Further from the shoulder joint.</td>
</tr>
<tr>
<td><strong>Hemiparesis</strong></td>
<td>Semi-paralysis occurring in one side of the body.</td>
</tr>
<tr>
<td><strong>Ipsi-lateral</strong></td>
<td>Same side.</td>
</tr>
<tr>
<td><strong>Lesion</strong></td>
<td>Site of injury in the brain.</td>
</tr>
<tr>
<td><strong>Neuron</strong></td>
<td>Basic functional unit of the Human Nervous System.</td>
</tr>
<tr>
<td><strong>Paresis</strong></td>
<td>Paralysis</td>
</tr>
<tr>
<td><strong>Proximal</strong></td>
<td>Closer to the shoulder joint.</td>
</tr>
<tr>
<td><strong>Sensorimotor</strong></td>
<td>Sensory input processed resulting in motor (movement) output.</td>
</tr>
<tr>
<td><strong>Uni-lateral</strong></td>
<td>Single side (left or right)</td>
</tr>
</tbody>
</table>