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INTRA- AND INTER-RATER RELIABILITY OF MAXIMUM TORQUE APPLIED DURING PASSIVE ELBOW RANGE OF MOTION TESTING POST-CASTING OF SUPRACONDYLAR AND LATERAL CONDYLAR FRACTURES IN CHILDREN

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Education
at the University of Kentucky

By

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ABSTRACT OF THESIS

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Elbow fractures account for a significant number of pediatric orthopedic injuries. The most common of these are the supracondylar and lateral condylar humeral fractures. When surgical repair is necessary casting and pinning of the elbow can affect the elbow's range of motion (ROM), so recovery is monitored. Practices for measuring recovery are not standardized so measures may not be consistent. A possible novel measure to help account for different clinicians participating in the same study is maximum torque applied during elbow end ROM testing. This study uses several comparisons of maximum torque applied by three different clinicians during end ROM testing on a sample of twenty-seven pediatric patients. Multiple mixed ANCOVAs and pairwise comparison models of maximum torque applied to assess the reliability of applied torque. Significant differences were only detected during six-month follow up appointments, and the twelve-month post-cast removal follow-up appointment. Significant differences in torque applied during tests of both flexion and extension end ROM of both the involved and uninvolved limb were seen mostly attributed to one participating rater. A paired t-test was conducted between the maximum torque measures taken during tests of both the involved and uninvolved limb. No significant difference was found in maximum applied torque. In addition, a two-sample t-test comparing the mean differences in maximum torque applied during the end ROM tests by the same or by different clinicians found no significant difference. While differences were noted in the pairwise comparisons between rater one and the other two during later appointments this could be because of the experience of this one rater with the test and their level of comfort performing it when further removed from incident of injury. If future studies on maximum torque in passive elbow ROM testing are carried out a larger group of patients will be needed to make comparisons between raters and visits. Other studies could also use multiple raters at one visit allowing for a direct comparison of maximum torque.

KEYWORDS: Elbow Flexion Extension, Passive ROM, Maximum Torque.

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Date

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CHAPTER 1. INTRODUCTION

1.1 Background

Elbow fractures are a common injury in children and if not treated appropriately can restrict an elbow's range of motion (ROM) and have a negative impact on quality of life. A study that examined records of 212,383 children under the age of sixteen who visited the hospital within a four-year period for a fracture found that 16% had suffered an elbow fracture, the second most common fracture after those of the wrist at 30% (Issin et al., 2015). Further studies reveal that 67% or 69.1% of the elbow fractures seen in pediatric populations were supracondylar and lateral condylar fractures (Landin et al.1986; Houshian et al., 2011).

Complications occurring in surgeries generally result in temporary loss of motion or permanent contractures of the elbow. One of the parameters measured by clinicians post-surgery and cast removal is the elbow's passive ROM. In most cases, 90% ROM in comparison to the non-operative side is considered a successful recovery (Zoints et al., 2009). One study that followed twenty-seven children with either supracondylar or lateral condylar fractures of the humerus found that 90% range of flexion and extension returned in 29.5 and 39.0 days respectively (Wang et al., 2009). Another study found that six weeks post-surgical repair or two to three weeks after cast removal all pediatric patients were at an average of 86% of the total ROM of the unaffected arm (Zoints et al., 2009).

The universal plastic goniometer is the standard for ROM measures because of accessibility and convenience. However, studies have shown that a means of electronic measure is more accurate. One such study found an intertester minimal detectable difference threshold between five different testers increased from four degrees of flexion and six degrees of extension with a universal goniometer to ten degrees in both flexion and extension when a computerized method was used (Armstrong et al., 1998).

The use of motion capture is preferable to traditional goniometry ROM assessment because of precision and accuracy as well as eliminating the necessity of a handheld measurement device. The use of motion capture allows for observations of the difference in rater technique. One of the important variables in interrater elbow passive ROM testing is the amount of torque used to attain an end ROM measure. Maximum torque use by clinicians has never been examined because passive ROM testing conducted during motion analysis appointments are undertaken before motion capture markers are applied. With the use of motion capture, maximum torque applied at end ROM can be assessed using a handheld strain gauge while outfitted with a marker set that would be used during later testing. While there are studies that test inter- and intra-rater reliability when measuring ROM, no studies have examined maximum torque application during end ROM testing.

1.2 Objective

This study examines inter-rater and intra-rater reliability of torque applied during passive ROM testing of the pediatric elbow after a supracondylar or lateral condylar fracture repair through pining and casting. A mixed statistical model examining torque usage of each rater during each appointment, an analysis of the difference in torque use with the same patient on the involved and uninvolved limb, and examination of the difference in applied torque during measurement of passive flexion and extension end ROM of consecutive appointments with the same patient were conducted to assess inter- and intra-rater reliability.

1.3 Hypotheses

1.3.1 Hypothesis 1

There will be a significant difference in maximum applied torque during end ROM between raters.

1.3.2 Hypothesis 2

There will be no difference in intra-rater maximum applied torque between the involved and uninvolved elbow.

1.3.3 Hypothesis 3

When the same rater performs tests over two consecutive appointments the mean difference in applied torque will not be the same as the mean difference when tests are performed by two different raters.

CHAPTER 2. LITERATURE REVIEW

2.1 Epidemiology of Elbow Fractures

Elbow fractures are prevalent in children seen in emergency rooms. A study done in a Turkish metropolitan area examined the records of 212,383 children under the age of sixteen who visited the hospital for a fracture within a four-year span and found that sixteen percent had suffered an elbow fracture; the second most common fracture after those of the wrist at thirty percent (Issin et al., 2015). Due to the prevalence of elbow fractures, research has been undertaken to identify how the fractures occur and what kind of fracture is most common. In a study of 589 pediatric elbow fracture cases, 55% were supracondylar fractures and twelve percent were lateral condylar fractures (Landin et al.,1986). This is supported by a concurrent study of 355 pediatric elbow fractures where 57.5% were supracondylar fractures and 9.6% were lateral condylar fractures (Houshian et al., 2001). Yet another study on elbow fracture epidemiology with a total of 488 fractures found that 43.8% were supracondylar fractures and 22.3% were lateral condylar fractures (Okubo et al., 2019). All these studies found the mechanism for injury was falling from ground level or higher onto an outstretched arm with the elbow slightly bent (Landin et al. 1986; Houshian et al., 2001; Okubo et al., 2019).

2.2 Surgical Procedures in Elbow Fracture Repair

The prevalence of these fractures has been established and additional studies examined treatment of these injuries. Some elbow fractures can be left alone, and they will heal. However, one study that investigated the necessity of surgical intervention found that 41% of the supracondylar fractures and 48% of the lateral condylar fractures required surgery (Okubo et al., 2019).

The Gartland classification system is used to determine the necessity for surgical repair of supracondylar fractures. It includes three levels of classification: Type I being a fracture with no displacement; Type II being a fracture with anterior displacement but the cortex intact posteriorly; and Type III complete disassociation of the proximal and distal portions of the fracture. Inter- and intra-rater reliability of identifying the classification of fractures has proven reliable with twenty-eight surgeons identifying fractures of the same imaging consistently with an r value of 0.98 (Teo et al., 2019).

Treatment for supracondylar fractures classified as Gartland Types II and III in most cases require reduction and percutaneous pinning. Reduction is the movement of the proximal and distal pieces of the fracture into alignment, and percutaneous pinning involves the placement of Kirschner wires to stabilize the pieces of the fracture and keep them reduced while healing (Prashant et al., 2016). There is some discussion about how the Kirshner wires should be placed, whether one medial and one lateral to supply maximum stability, or two lateral wires to eliminate the possibility of damaging the ulnar nerve with the placement of a medial wire. Several studies have been conducted regarding percutaneous pin placement and only one has found medial-lateral pin placement more advantages whereas five studies have concluded that there is no significant advantage to either procedure (Prashant et al., 2016).

Treatment for lateral condylar fractures is similarly classified by the Weiss classification scale. The Weiss classification scale includes three specifications: Type I the fracture of the lateral condyle is intact and does not penetrate to the articular surface; Type II the fracture is displaced by at least 2mm and extends through the articular surface of the joint, typically meaning the fracture is held in place by the cartilage of the articular surface; and Type III the fracture is displaced by four millimeters or more and has some form of rotational displacement as well (Shroeder et al., 2020). Surgical intervention is generally considered to be necessary when the displacement of the fracture is more than two mm at any aspect of the separation. This is accomplished by either closed reduction, for which reduction is measured by intraoperative fluoroscopy, or open reduction, which is done with an incision, and measured by visual inspection and reduced. Fractures are considered reduced if the fracture less than two mm away from medial or lateral aspect of fracture. Fixation is accomplished with two or three Kirschner wires or a cannulated screw. Neither fixation method has shown advantages in recovery, except that canulated screw could speed recovery by reducing the length of time a cast should be worn (Shroeder et al., 2020).

2.3 Recovery Metrics

As noted in these studies, the ultimate purpose of surgical intervention is to restore form and function, namely, flexion, extension, and pronation, supination ROM. However, studies of post-operative procedures following elbow surgery are less detailed than those of operative procedures. Though the actual recovery statistics in these studies are helpful, they cannot be directly compared due to lack of consistent means of tracking recovery.

A few studies document the time to return of full ROM. A Zoints study was done on 63 patients who underwent surgical repair of a supracondylar fracture and whose recovery was monitored over a series of appointments at six weeks, twelve weeks, twenty-six weeks, and fifty-two weeks (Zoints et al., 2009). The ROM was measured by the same clinician with a standard plastic universal goniometer at each appointment. This study found that the total loss of ROM compared to the uninvolved limb showed mean movement losses of twenty-eight percent, fourteen percent, six percent, and two percent respective to appointment (Zoints et al., 2009). Additionally. A study tracking time to 90% full range of flexion and extension of sixteen children with lateral condylar fractures and twenty-nine with distal forearm fractures found the average time to return to 90% flexion was 39.0 days for those with lateral condylar fractures and 35.6 days for those with distal forearm fractures; the days for return to 90% flexion were 39.5 and 30.2 respectively (Wang et al., 2009). Lastly, a Bernthal study used relative arc motion percentage at time points of cast removal, six weeks, twelve weeks, eighteen weeks, twenty-four weeks, and forty-eight weeks post cast removal and found relative arc motion percentages of 44%, 84%, 87% 93% and 97% respectively (Bernthal et al., 2011). Another study using relative arc motion percentage concluded that age had a significant effect. Those older than five years of age showed a three to nine percent decrease in total arc motion at a 48 week follow up appointment post cast removal (Spencer et al., 2010).

Because restoring the function of the elbow after surgery is the main purpose of elbow surgery, it is important to measure ROM. However, a wide range of assessments can be used to measure recovery. Some use active ROM, some use total reach and others use passive ROM. Active and passive ROMs are both measured by goniometry. There are several different ways to perform an active ROM test by goniometry as analyzed by Petherick et al. (1988). They used both universal goniometry and fluid goniometry to assess active ROM of the elbow in a healthy population when two different raters are used. Fluid goniometry proved more reliable in this active test situation with an R^2 value of 0.92 while universal goniometry had an R^2 value of only 0.52. Significant differences are also seen between the two methods (Pertherick et al., 1988). With training, universal goniometry can achieve measures that are reliable with accuracy within ten degrees of flexion and extension. However computerized goniometry was found more accurate with accuracy within four degrees flexion and six degrees extension (Armstrong et al., 1998).

The current practice of measuring elbow passive ROM is universal goniometry. This is most common because of its simplicity and accessibility, using a clear plastic gauge, and boney landmarks to assess the ROM. The landmarks used are the acromion to establish the midline of the humerus, the radial styloid process to establish the midline of the forearm, and the lateral epicondyle of the humerus (Norkin et al., 2003). Intra- and inter-rater reliability of a universal goniometer has been found to be a statistically reliable method for measurement of elbow ROM. In a study of 352 healthy individuals of age 18-79 years, passive and active ROM in all participants was measured by the same person three times through universal goniometry; standard error measure (SEM) of active flexion and extension was three degrees and two degrees respectively with a smallest detectable difference (SDD) calculated at seven degrees with respect to flexion and six degrees in extension (Zewurs et al., 2017). Passive ROM results were similar with SEMs of seven and five degrees and SDDs of eight and nine degrees. This suggests that intra-rater reliability for universal goniometry is acceptable when using one clinician**.** In the same study, inter-rater comparisons were made using twenty elbows and two clinicians which yielded similar success with SMEs less than or equal to two degrees and SDDs equal to or greater than four degrees (Zewurs et al., 2017).

Universal goniometry has also been favorably compared to other methods of range of motion measurements. A study comparing universal goniometry and radiographic measurements found that in a group of 102 elbows assessed three times by the same clinician yielded 0.954 and 0.973 ICC in flexion and extension respectively, and absolute maximal error between goniometry and radiographic measurement seven degrees in flexion and ten degrees in extension. In addition, the maximum deviation of elbow flexion and extension when compared to radiographic images was ten percent (Chapleau et al., 2011). Inter-rater reliability was consistent in two studies that examine ROM with a universal goniometer of thirty-eight healthy females and twenty-two female handball players with the latter showing an ICC of 0.94 and SEM of 1.06 degrees (Armstrong et al., 1998; Fiesleser et al., 2015). These studies conclude that universal goniometry is an acceptable clinical measurement tool in elbow ROM when used by one or more clinician(s).

Reliability between methods of goniometry however have shown inconsistency (Armstrong et al., 1998; Petherick et al., 1988). Armstrong studies three goniometric methods; universal, computerized, and mechanical testing devices are used to assess flexion and extension passive ROM. Each method is reliable within testing method, but when compared with a differing method, a significant difference in ROM is detected (Armstrong et al., 1998). Similarly, a study involving twenty-three healthy females and the use of universal, fluid, and electromagnetic goniometers finds that it is inadvisable to use multiple methods of measurement in the same institution because of significant differences in measurements when using different methods (Petherick et al., 1988). Universal goniometry, therefore, is the primary method of measurement today because of its reliability and availability.

The most common measurement technique for activities of daily living is three-dimensional (3D) motion capture. After an exhaustive search, no studies were found comparing universal goniometry and 3D motion capture of the elbow, but 3D motion capture has been compared in hip and knee passive goniometric measures and with findings of high correlations between all measures. The variability within the motion capture group is lower than that of the goniometric measures indicating that motion capture is an appropriate method to conduct a passive ROM test of the lower limb and shows higher precision than that of universal goniometry (Yazdifar et al., 2013). The strong correlation between these two methods of testing occurs because the same boney landmarks are used in the tests. However, a direct comparison of the two methods may not yield statistically similar results because even though similar landmarks are used the elbow joint center is extrapolated and any motion in the other two planes of motion is accounted for during 3D motion capture. The Armstrong study observed significant statistical differences between universal goniometry and 3D motion capture and concluded that only one method should be used through the course of a single study (Armstrong et al., 1998).

Motion capture has been used widely for active range of motion studies and various marker sets have been used to examine the movement of the elbow. Valevicius et al. (2018), reviewed sixteen upper body kinematics studies that utilize optical motion capture. Eight of these studies used strictly anatomical marker sets Cimolin et al.,2012; Hebert et al., 2014; Murgia et al., 2010; Murphy et al., 2006; Pereira et al., 2012; Petuskey et al., 2007; Rab et al., 2002; Ricci et al., 2015), four used only clusters of markers (Dennerlein et al., 2007; Jaspers et al., 2011; Qin et al., 2011; Qin et al., 2014), and four used a combination of the clusters and anatomical markers (Cowley et al., 2016; Lobo-Prat et al., 2012; Reid et al., 2010; Schmidt et al., 1999). All studies which used anatomical marker sets used a shoulder marker, twelve marker sets used the acromion (Cimolin et al., 2012; Cowley et al., 2016; Hebert et al., 2014; Murgia et al., 2010; Murphy et al., 2006; Pereira et al., 2012; Petuskey et al.,2007; Rab et al., 2002; Reid et al., 2010; Ricci et al., 2015), and two used an anterior and posterior deltoid marker (Lobo-Prat et al., 2012; Reid et al., 2010). Four studies used only the lateral epicondyle of the humerus (Cimolin et al., 2012; Murphy et al., 2006; Petuskey et al., 2007; Rab et al., 2002) and seven used the medial and lateral epicondyle of the humerus (Cowley et al., 2016; Hebert et al., 2014; Murgia et al., 2010 Pereira et al., 2012; Ricci et al., 2015;

Schmidt et al., 1999). One study did not use either epicondyle marker and relied on clusters for elbow joint measures (Reid et al., 2010). Either the ulnar styloid or the radial styloid was used in some combination for all twelve anatomical marker sets (Valevicius et al., 2018). While motion capture is the primary method of active ROM measures during dynamic tasks, the marker sets used to attain this information vary quite a bit and are difficult to evaluate against one another. Therefore, the use of anatomical marker set, or clusters depend on multiple factors including the movement being evaluated and the time constraints of a study appointment.

To accurately measure elbow flexion and extension, and pronation and supination, the placement of reflective motion capture markers must be considered. A study performed with 12 healthy males utilized an anatomical marker set of right acromion center, left acromion center, lateral epicondyle, medial epicondyle, radial styloid, ulnar styloid, distal head of the 5th metacarpal, distal head of the 2nd metacarpal, clusters on the arm and forearm, and one with just marker clusters (Wang et al., 2019). This study found that pronation and supination measures differed by 14.9% and 43.2% respectively and differed by 5.3% and 9.1% in flexion and extension. This study concludes that the most appropriate marker set to measure elbow motion is a strictly anatomical marker set, due to the increased movement artifact introduced by cluster markers (Wang et al., 2019). Since the introduction of motion capture in combination with force plates, kinetics including joint torque has been measured during dynamic movements. This has been accomplished by contact of the studied limb to a force platform. When doing passive ROM testing little has been done to examine kinetics applied to a patient during testing. This testing could shed light on consistency in torque used during testing with multiple raters, a critical factor in passive ROM testing and could be used to ensure consistency between raters involved in clinical studies. One important factor during studies using handheld force devices is protocol adherence. Handheld strain gauges have however proven effective in passive moment testing of the knee with the hip in 90 degrees flexion and 0 degrees flexion as well as the ankle with the knee at 90 degrees flexion and 0 degrees flexion, when the dynamometer is aligned perpendicularly with the segment being manipulated using a multidirectional strain gauge. When a force vector is simplified and assumed perpendicular the measured passive moment can be altered by as much as ten percent (Koussou et al., 2022). This suggests that with the use of a handheld strain gauge that has multidirectional force transducers, torque could be calculated accurately if the contact of the gadge is flush with the forearm. This torque could be used as a measure of consistency in both intra- and inter-rater reliability between multiple appointments. As well as when the measured passive ROM is expected to increase, or between an involved limb and uninvolved limb that will have obvious difference in ROM.

CHAPTER 3. METHODOLOGIES

3.1 Recruitment and Participants

In conjunction with a larger study conducted with patients at Shriner’s Hospital for Children Lexington, who underwent elbow repair surgery at UK Hospital or Shriner’s Hospital for Children Lexington. Patients were referred to the motion analysis lab by their operating physician. This study was conducted with an approved IRB and all participants recruited consented to participate before they were first seen at the Shriner's Hospital for Children Lexington motion analysis center.

Children of 4-12 years of age seen at Shriner's Hospital for Children Lexington Kentucky campus who had previously had supracondylar or lateral condylar humeral fractures and surgical repair were recruited for this study by their physicians at the time of cast removal. Twenty-seven patients were admitted to this study with an average age of 7.3 years detailed demographics regarding participants appear in table 3.1.

Table 3.1 Participants' demographics.
Age: mean in years (Standard deviation), gender: m: male f: female, Fracture type: Supr: Supracondylar Lat: Lateral condylar, Visit 3: patients who attended first round of passive ROM testing 3 months post cast removal, Visit 4: patients who attended passive ROM testing 6 months post cast removal (patients who also attended visit 3), Visit 5: patients who attended passive ROM testing 12 months post cast removal (patients who also attended visit 4).

Number of participants	27
Age yr (SD)	7.3(1.8)
Gender m/f	17/10
Fracture type supr/lat(requiring surgery)	14(11)/13(7)
Visit 3	16
Visit 4	11(7)
Visit 5	15(8)

3.2 Measurements

As part of a larger study there were a total of 5 visits to the motion analysis lab. Measurement for passive ROM flexion and extension of both the involved and uninvolved elbows was conducted beginning with the third visit, at three approximate time periods after cast removal three months (Visit 3), six months (Visit 4), and twelve months (Visit 5).

Each measure is taken with the use of an ATMI manual strain gauge (Model He2.5D-50 Waterton MA) that is synchronized with the motion capture system. Applied torque is obtained from force data once end ROM is achieved, and the joint angle remains stable. Maximum applied torque is estimated at end range for each movement by calculating the cross product of the applied force vector and the vector defined by the moment arm segment between applied force and the elbow joint center. The elbow joint center was derived from the medial and lateral epicondyle elbow markers. A diagram of this equation is illustrated in figure 3.1. Clinicians were asked to keep the strain gauge perpendicular to the forearm during the entirety of the test as much as possible to simplify the calculation of torque from force during the test. The strain gauge with two markers is shown in figure 3.2.

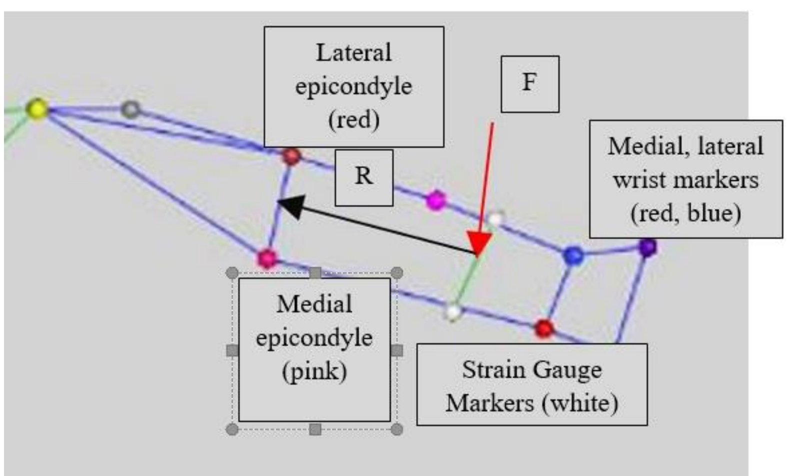

Figure 3.1 Elbow Extension Torque Diagram.
The red arrow is the perpendicular force vector (F) of the strain gauge, and the black vector (R) is the moment arm, torque was derived by calculating the cross product of these two vectors (T = RXF).

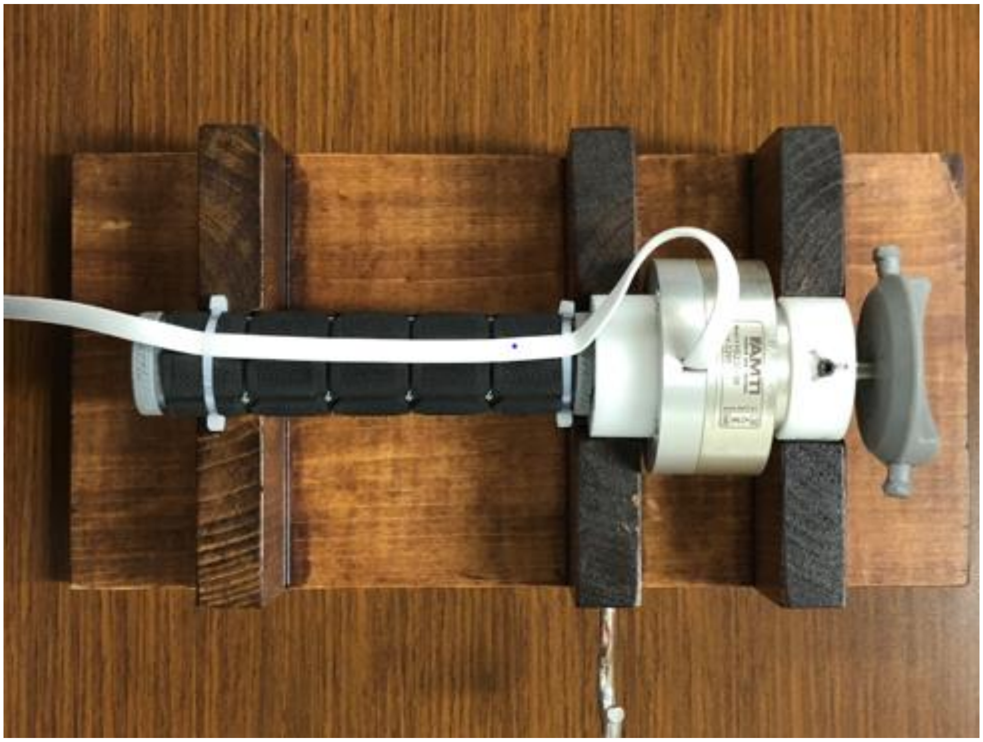

Figure 3.2 AMTI model HE2.5D-50 with reflective markers.

Measurements were all conducted by motion capture utilizing Cortex software and a twelve 3D motion capture camera array (Motion Analysis Corporation, Eagle Cameras, Rohnert Park, CA). The marker set used was as follows: markers are placed on the anterior and posterior shoulder, bisecting the arm at the level of the axilla. A bicep offset was placed on the lateral aspect of each arm. Markers were placed on medial and lateral elbow, bisecting the humeral epicondyles while the elbow was in full extension. A marker was placed as a forearm offset on the lateral forearm, in line with the thumb. Markers were placed on the medial and lateral wrist, bisecting the wrist joint, the medial and lateral hand on the distal end of the pointer finger, and little finger metacarpal bones. Lastly, an offset marker was placed on the left anterior chest. A table of these markers is detailed below (table 3.2) and a static and active stick are shown in model (figure 3.3 and figure 3.4).

Table 3.2 Marker Locations.

All markers are bilateral except those indicated

Marker Location	Placement Guidelines
Anterior and Posterior Shoulder	Bisecting the arm at the level of axilla
Upper Arm Offset	Lateral arm between shoulder and elbow markers
Medial and Lateral elbow	Bisecting the humeral epicondyles
Forearm Offset	Radial side between elbow and wrist markers
Medial and Lateral Wrist	Bisecting the wrist joint
Medial and Lateral Hand	Distal end of the 2^{nd} and 5^{th} metacarpal bones
Left Anterior Chest offset *unilateral only	Lateral to sternum on left side
Force Transducer	One maker on either side of the head of the force transducer

A static capture was then taken with the patient sitting with shoulders slightly abducted and the palms facing forward with the strain gauge sitting at their feet with the two markers visible to account for it in future captures to define its position (Figure 3.3).

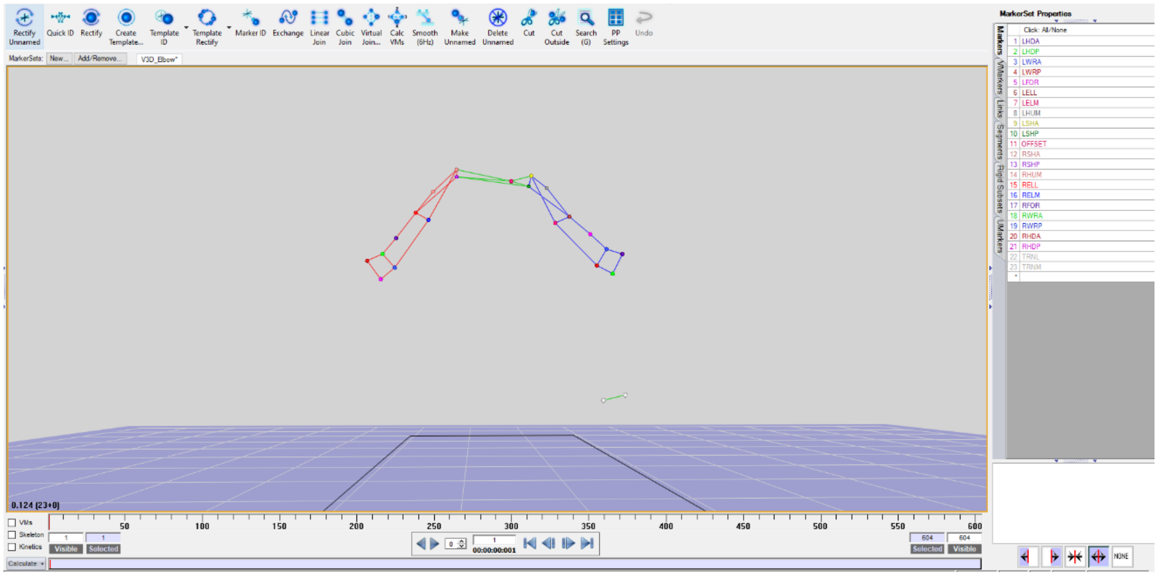

Figure 3.3 Static Calibration Trial.
Green- shoulder, red- right arm, blue- left arm

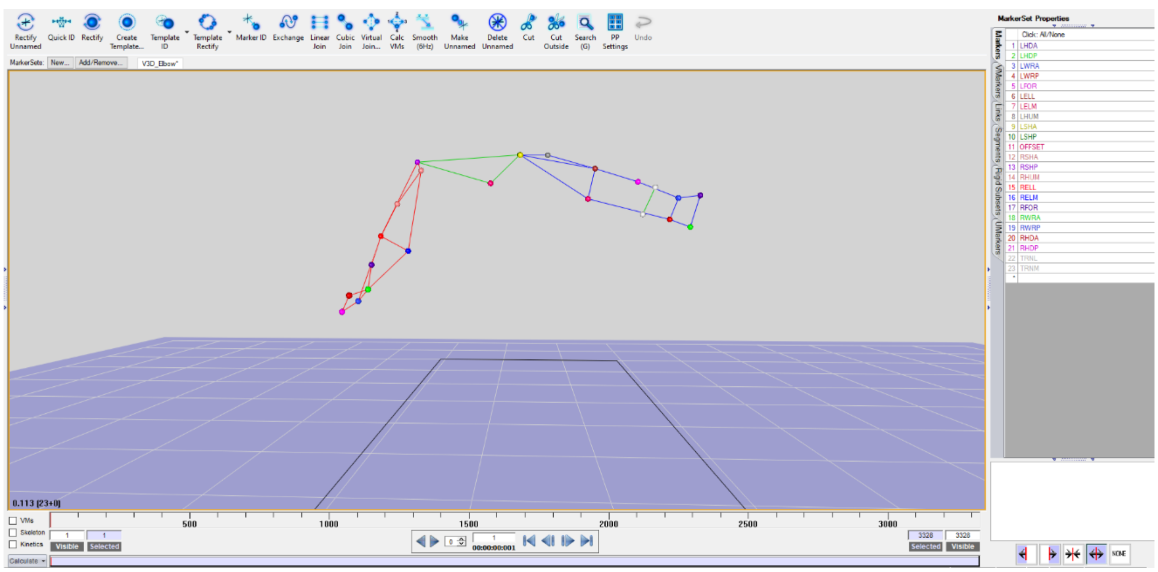

Figure 3.4 Left Elbow Passive Extension Trial.
Green-shoulder, red- right arm, blue left arm, Transducer- green line with 2 white markers.

3.2.1 Passive Elbow Flexion ROM Procedure

Passive elbow flexion was measured five times beginning with the uninvolved arm with the patient seated on a bench with the shoulder flexed at 45 degrees, and slightly abducted. The arm was then flexed to a comfortable end range with the forearm supported by the therapist performing the passive ROM measure. End range was determined by the therapist as end feel, either by the contact of anterior muscle bulk or tension in the triceps brachii. It should also be mentioned that once end range was reached the angle of the elbow remained constant. After the end range was reached, more force was applied by the therapist to ensure the end range was achieved. Force was administered to the arm by the therapist through the handheld strain gauge perpendicular to the arm to measure force simultaneously with passive elbow flexion angle throughout the test. Torque was only extrapolated when end range was reached, and the elbow angle was constant. Maximum torque was obtained by taking the maximum force vector while at end range and calculating the cross product of that vector and the vector defined by the moment arm defined by the center of the strain gauge and the elbow joint center. Measurements were taken with the therapist seated next to the patient to ensure the visibility of all markers during the duration of the test. Motion capture was started with the patient's elbow flexed at 90 degrees for ease of marker identification and end ROM was measured. The same procedure was repeated for the involved arm.

End range in flexion was measured on the involved limb followed by the uninvolved. The five trials of elbow end ROM and maximum torque applied by the therapist to attain end range was then averaged to constitute the clinical measure.

3.2.2 Passive Elbow Extension ROM Procedures

Passive elbow extension was measured similarly with the patient seated on a bench with the arm at a comfortable extension the shoulder slightly abducted and flexed at 45 degrees. The therapist then performed five repetitions of passive extension by pushing on the arm with the strain gauge perpendicular to the arm. End range was considered achieved with either a soft stop caused by eccentric contraction of the biceps brachii or hard stop by the contact of the olecranon process of the ulna with the olecranon fossa of the humerus. When end feel was reached the therapist applied a little bit more force to ensure end range was reached.

As with the flexion measurements, the uninvolved limb was measured first followed by the involved limb. Averages were then taken from the five trials to establish a clinical measure for passive elbow extension end ROM, and maximum torque applied by the therapist to attain end range.

3.3 Data Analysis

Because of the limitations of a clinical setting, only one rater was available to be used at each appointment, so a direct comparison of raters was not feasible. A mixed statistical model was attempted with the rater as the independent variable and maximum torque as the dependent variable with the days in between each appointment as an explanatory variable. To accomplish this an ANCOVA model was constructed when a statistically significant difference was detected among the raters during a specific test during a round of testing, a pairwise comparison was then conducted to isolate which rater(s) accounted for the detected difference.

Maximum torque was compared between the involved and uninvolved limb using a paired two tailed t-test. This was able to be done because both the involved and uninvolved limbs were tested at each appointment.

With a limited number of participating patients, pairwise comparison between two consecutive appointments was not feasible. Instead, a difference in the clinically measured mean maximum torque was calculated between each consecutive appointment and days between appointments. This was factored in as an explanatory variable. Mean difference was assessed in two groups: one single rater and two different raters when performing both tests. These two groups were analyzed using a t-test to compare the means with an alpha level of ≤ 0.05.

CHAPTER 4. RESULTS

4.1 Therapist Applied Maximum Torque

Results of multiple ANCOVA models to test the difference between the three raters at the three time points and with each limb, with maximum applied torque as the dependent variable and rater as the independent variable showed no significant difference between raters during visit three in either flexion or extension end ROM tests. For visit four, only the ANCOVA constructed for the involved limb during extension range of motion testing yielded statistically significant results ($p = 0.026$). All other results for visit four were not statistically significant. Visit 5hadthe largest discrepancy between raters with significant or near significant results in three of the four different ANCOVA models; results were statistically significant for uninvolved flexion testing ($p = 0.045$), involved extension testing ($p = 0.0008$) and near significant enough to examine with a pairwise comparison in uninvolved flexion testing ($p = 0.068$). Table 4.1 presents the results of all ANCOVA models comparing torque applied by the different raters.

Table 4.1 Maximum Torque vs. Rater.
Adjusted for days since previous visit. ***p-value is from ANCOVA models that adjust 6 month and twelve-month visits estimates for the number of days since previous visit. * p-values indicate significant or near significant differences in maximum torque use in each model, that could possibly show significant differences when examined through a pairwise analysis.

Visit	Type	Limb	Rater *p*-value
Visit 3 3 Month	Flexion	Involved	0.272
		Uninvolved	0.625
	Extension	Involved	0.219
		Uninvolved	0.456
Visit 4 6 Month	Flexion	Involved	0.266
		Uninvolved	0.241
	Extension	Involved	0.026*
		Uninvolved	0.891
Visit 5 12 Month	Flexion	Involved	0.908
		Uninvolved	0.045*
	Extension	Involved	0.0008*
		Uninvolved	0.068

When an ANCOVA model resulted in a significant difference, a pairwise analysis of the significant values was then conducted. During visit 4 testing of involved limb extension the torque applied by rater 1 was significantly greater than that of raters 2 and 3 (p = 0.018, p = 0.012).

The significant differences observed during visit five were many. Maximum applied torque during flexion of the uninvolved limb showed significant differences between rater 2, and the others (p=0.037, p=0.025), there was no significant difference between raters 1 and 3. During flexion passive ROM of the involved limb rater 1 used a significantly greater amount of torque than raters 2 and 3 (p=0.003, p=0.0002), there was no significant difference between 2 and 3. Extension of the uninvolved limb showed significant differences between rater 1 and rater 3 (p=0.037), there was no significant difference between raters 2 and 3. Table 4.2 presents a full break-down of all pairwise comparisons.

Table 4.2 Pairwise comparisons
Comparisons between raters of significance tests during the ANCOVA test. * Indicate significant p-values of pairwise comparison.

Visit, Test, Limb	Rater Pair	Difference Estimate (Nm)	p-value
Visit 4, Extension, Involved Limb	1 vs. 2	2.71	0.018*
	1 vs. 3	3.08	0.012*
	2 vs. 3	0.37	0.599
Visit 5, Flexion, Uninvolved Limb	1 vs. 2	-1.40	0.037*
	1 vs. 3	-0.05	0.931
	2 vs. 3	1.35	0.025*
Visit 5, Extension, Involved Limb	1 vs. 2	2.25	0.003*
	1 vs. 3	3.14	0.0002*
	2 vs. 3	0.89	0.089
Visit 5, Extension, Uninvolved Limb	1 vs. 2	0.44	0.601
	1 vs. 3	1.95	0.037*
	2 vs. 3	1.51	0.069

4.2 Maximum Torque Difference Between Involved and Uninvolved Limbs

A paired sample t-test was conducted on the maximum torque applied during end ROM testing for the involved limb compared to the uninvolved limb, for each time point in the study. Results showed no significant difference in torque used during end ROM testing of either flexion or extension, between the involved and uninvolved limb. These results are summarized in table 4.3 below.

Table 4.3 Paired sample T-test
Result of end ROM maximum torque for the involved and uninvolved limb with an alpha level of 0.05 included is mean torque± the standard deviation.

Visit #	Type	Involved Limb Maximum Torque (Nm)	Uninvolved Limb Maximum Torque (Nm)	Paired t-test *p*-value
Visit 3 (3 month)	Flexion	2.66 ± 1.53	2.80 ± 1.70	0.535
	Extension	3.12 ± 2.08	2.94 ± 1.60	0.613
Visit 4 (6 month)	Flexion	2.71 ± 1.39	3.25 ± 1.07	0.081
	Extension	2.97 ± 1.47	2.92 ± 1.09	0.909
Visit 5 (12 month)	Flexion	2.76 ± 0.89	2.57 ± 0.89	0.493
	Extension	2.89 ± 1.36	3.03 ± 1.24	0.617

4.3 Maximum Torque Difference Between Consecutive Appointments

An analysis of the mean difference of torque applied by the same or by different raters between consecutive testing visits was conducted. The time between appointments was accounted for and no significant difference was found so the comparison of mean difference in torque was deemed acceptable. There were no significant differences in the mean difference of torque used whether it was the same therapist conducting the test or not (alpha level of .05). This is true for all pairs of visits and for both flexion and extension end ROM tests. All of these are presented in table 4.4 and figures 4.1-4.10.

Table 4.4 Difference in maximum use in consecutive visits single vs. multiple raters. Difference for visits 3 & 4 were calculated: Maximum torque visit 3- Maximum torque visit 4. Differences for visits 4 & 5 were calculated: Maximum torque visit 4- Maximum torque visit 5.

Visit #s	Type	Limb	Mean Same Rater Difference in Maximum torque (Nm)	Mean Separate Rater Difference in Maximum torque (Nm)	p-value
Visits 3 & 4	Flexion	Involved	0.143	0.035	0.7227
		Uninvolved	0.188	-0.155	0.435
	Extension	Involved	0.283	-0.025	0.7517
		Uninvolved	0.072	-0.150	0.6309
Visits 4 & 5	Flexion	Involved	0.154	-0.577	0.0737
		Uninvolved	-0.404	-0.847	0.3467
	Extension	Involved	0.934	-1.00	0.0579
		Uninvolved	-0.8770	0.334	0.0988

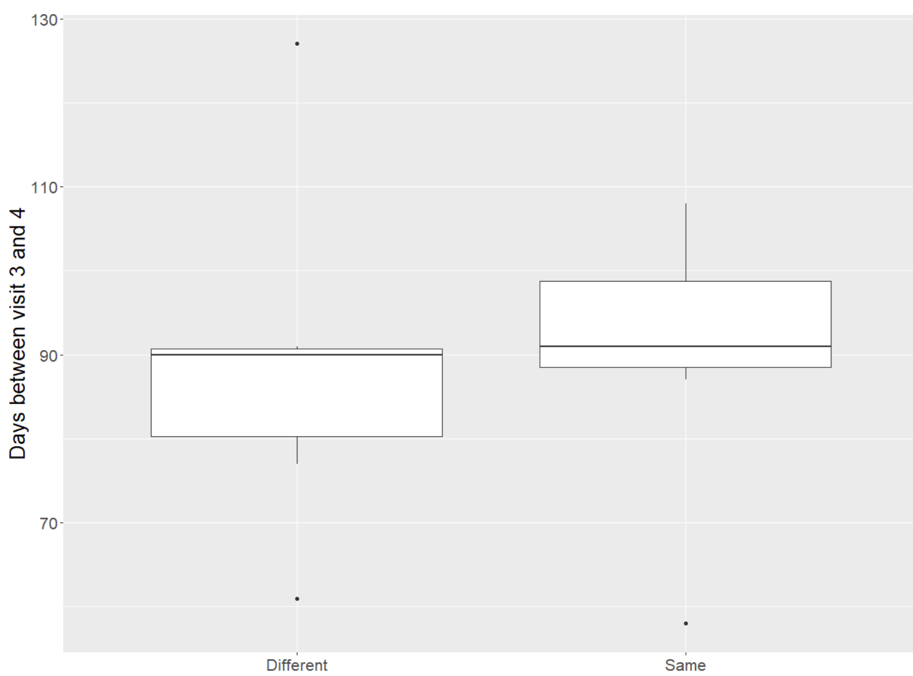

Figure 4.1 Days between visits 3 and 4 (Visit 3 and Visit 4) with the same or different therapists
Different: 155.71, Same: 152.43, p = 0.9121

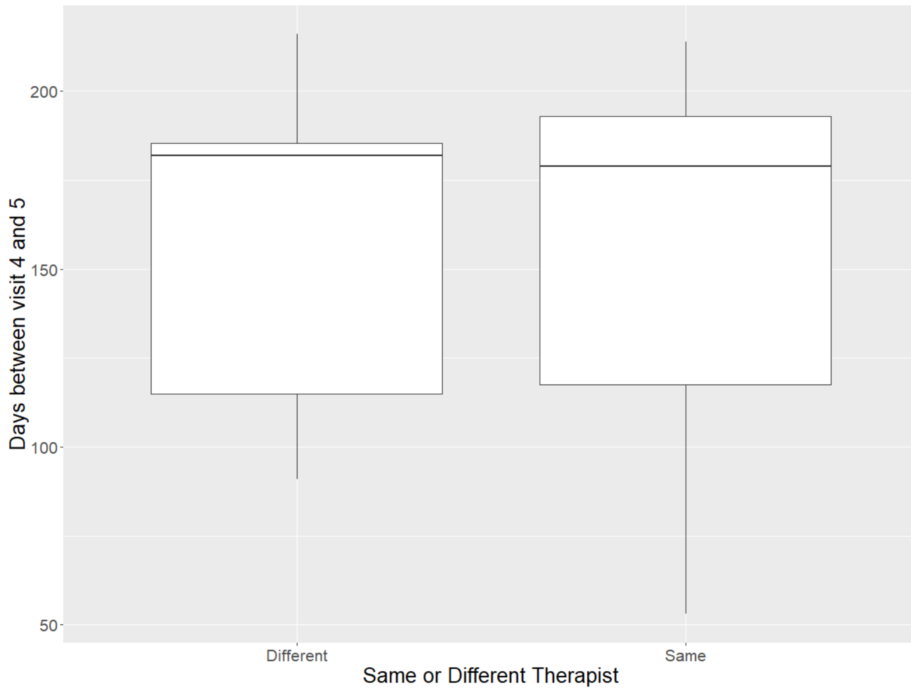

Figure 4.2 Days between visits 5 and 4 with the same or different therapists
Different: 155.71, Same: 152.43 p=0.9121

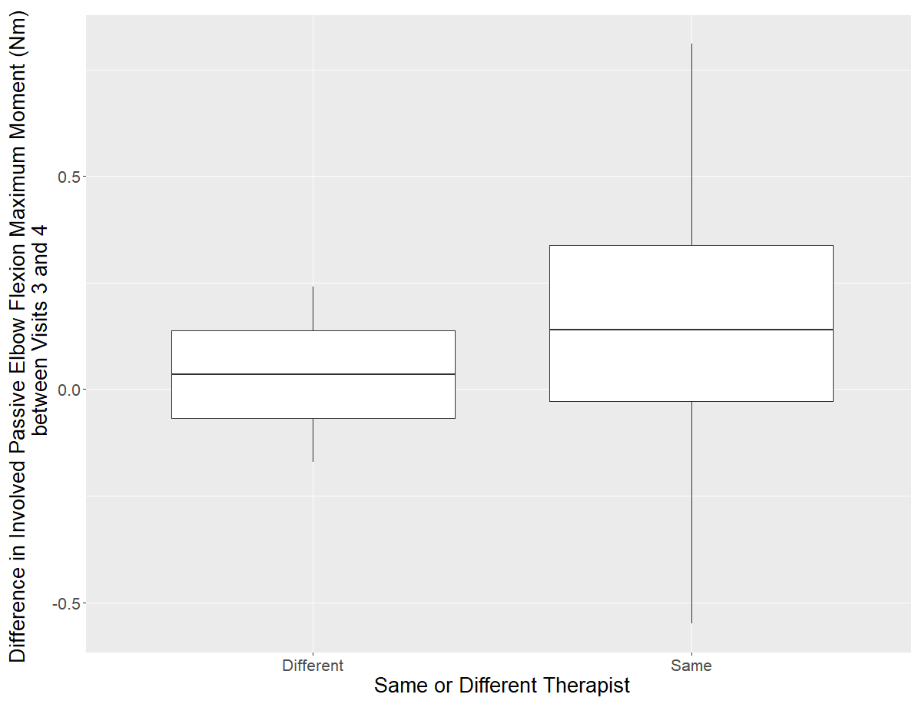

Figure 4.3 Mean change in involved passive elbow flexion, therapist applied Maximum torque between Visit 3 and Visit 4
Different: 0.035, Same: 0.143, p= 0.7227

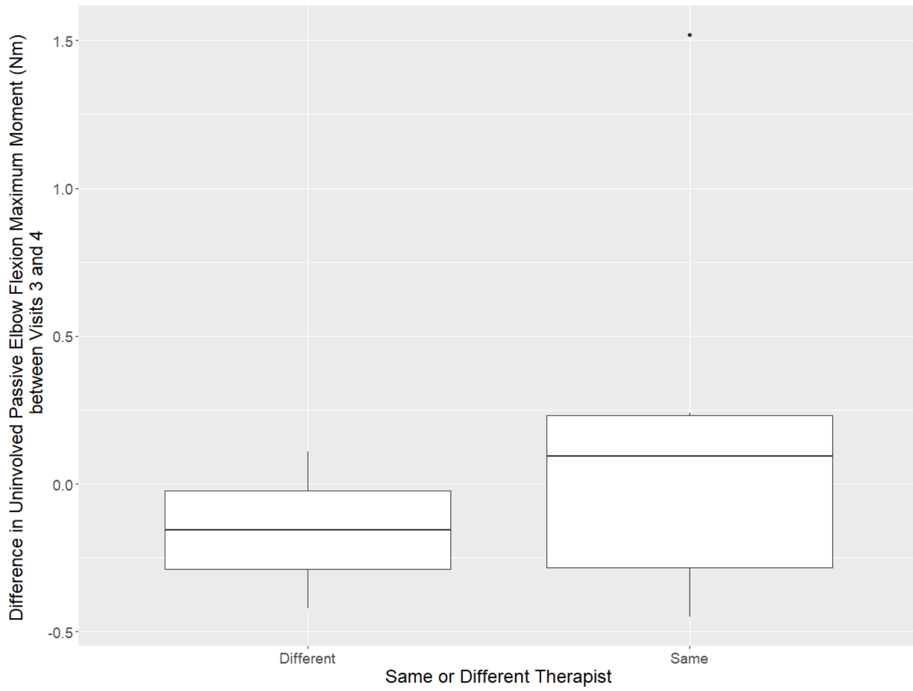

Figure 4.4 Mean change in uninvolved passive elbow flexion, therapist applied Maximum torque between Visit 3 and Visit 4
Different: -0.155, Same: 0.188 p=0.435

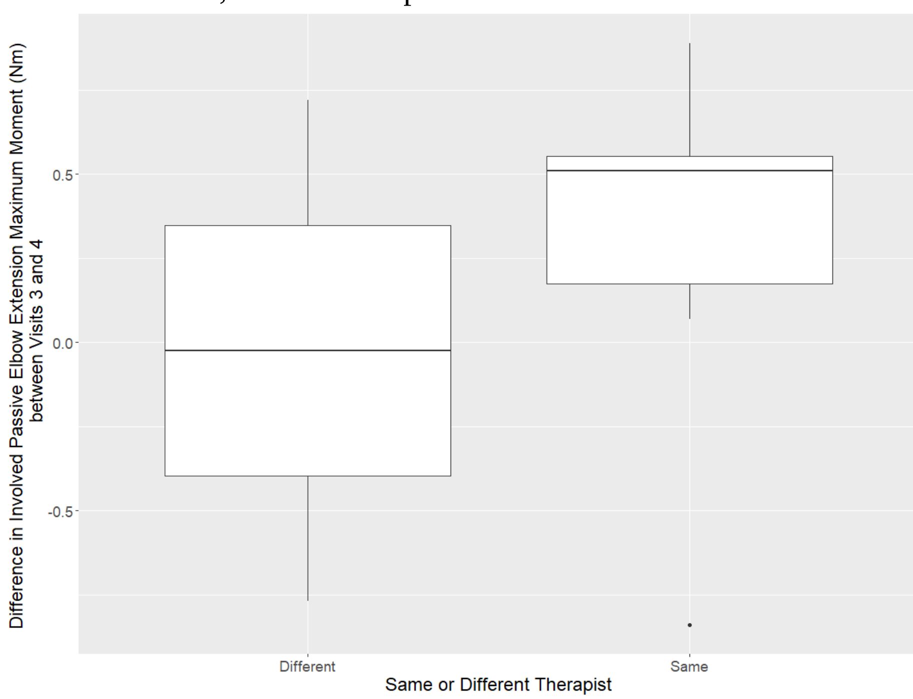

Figure 4.5 Mean change in involved passive elbow extension, therapist applied Maximum torque between Visit 3 and Visit 4
Different -0.025 Same: 0.283 p=0.7517

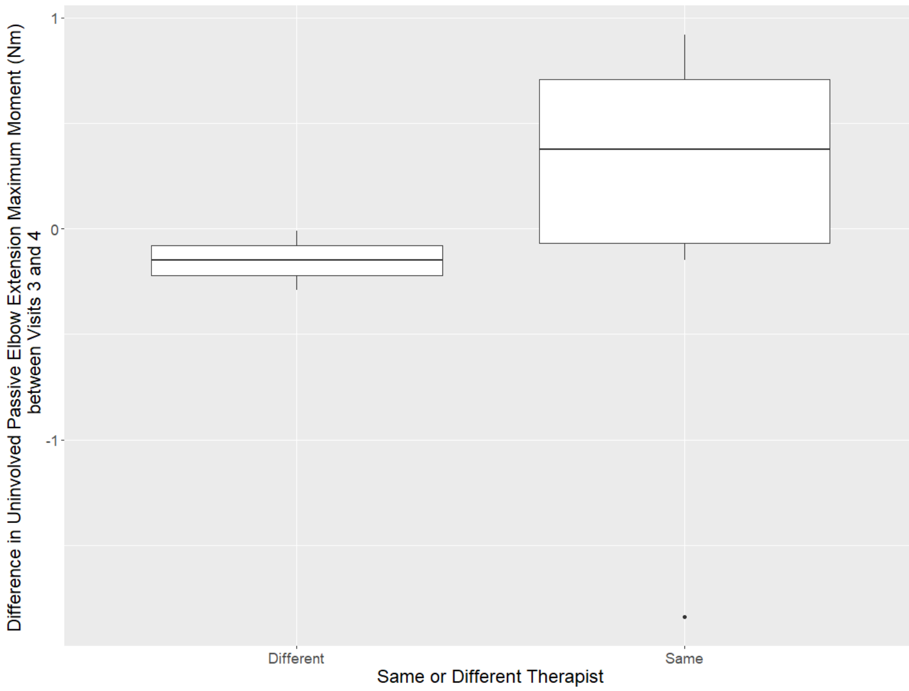

Figure 4.6 Mean change in uninvolved passive elbow extension, therapist applied Maximum torque between Visit 3 and Visit 4
Different-0.150, Same: 0.072, p=0.6309

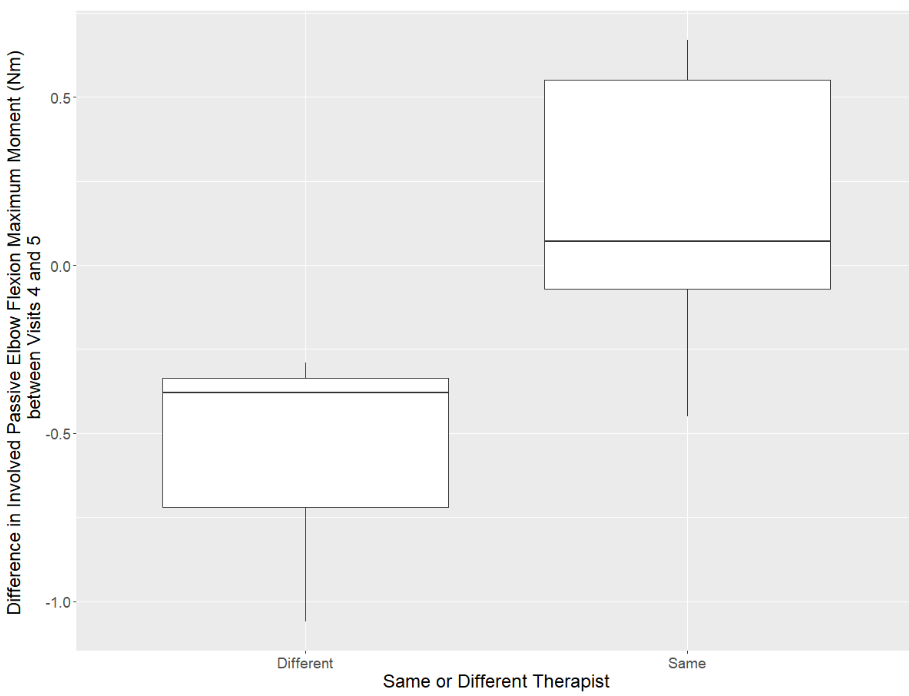

Figure 4.7 Mean change in involved passive elbow flexion therapist, applied Maximum torque between Visit 4 and Visit 5
Different: -0.577, Same: 0.154, p=0.0737

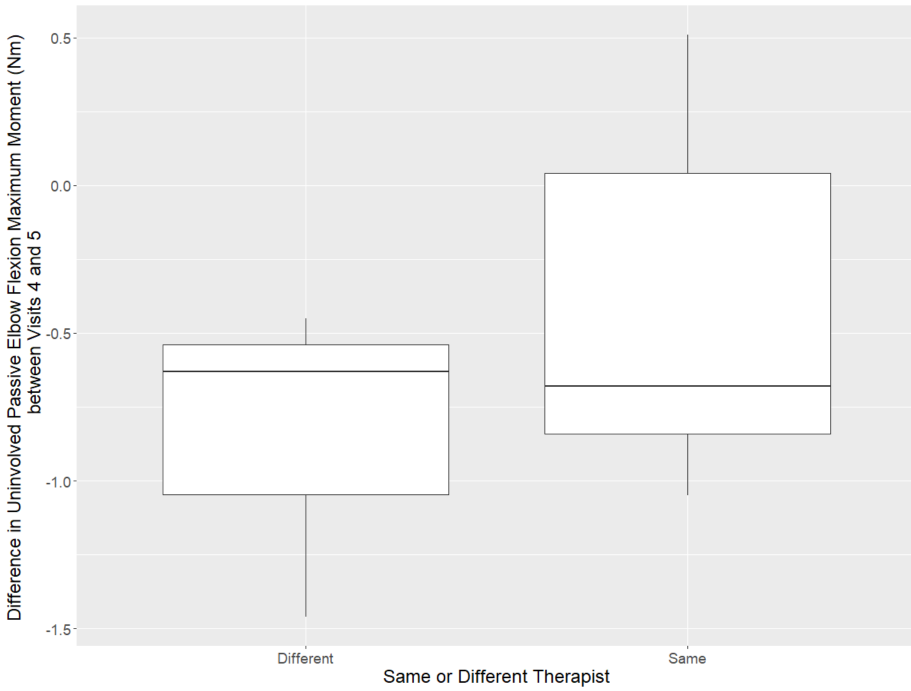

Figure 4.8 Mean change in uninvolved passive elbow flexion therapist, applied Maximum torque between Visit 4 and Visit 5
Different: -0.847, Same: -0.404, p=0.3467

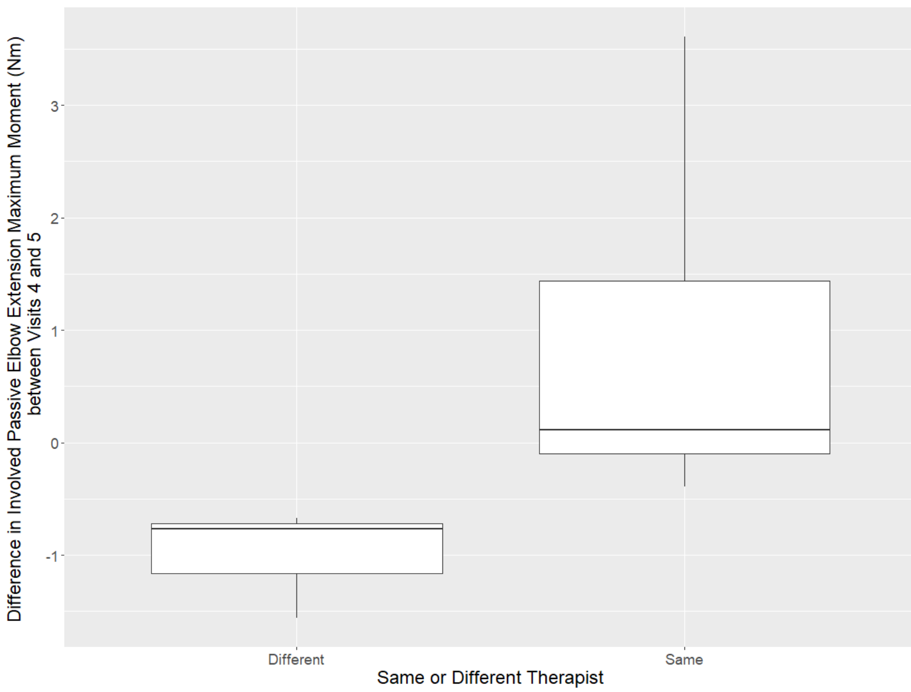

Figure 4.9 Mean change in involved passive elbow extension therapist, applied Maximum torque between Visit 4 and Visit 5
Different: -1.000, Same: 0.934, p=0.0579

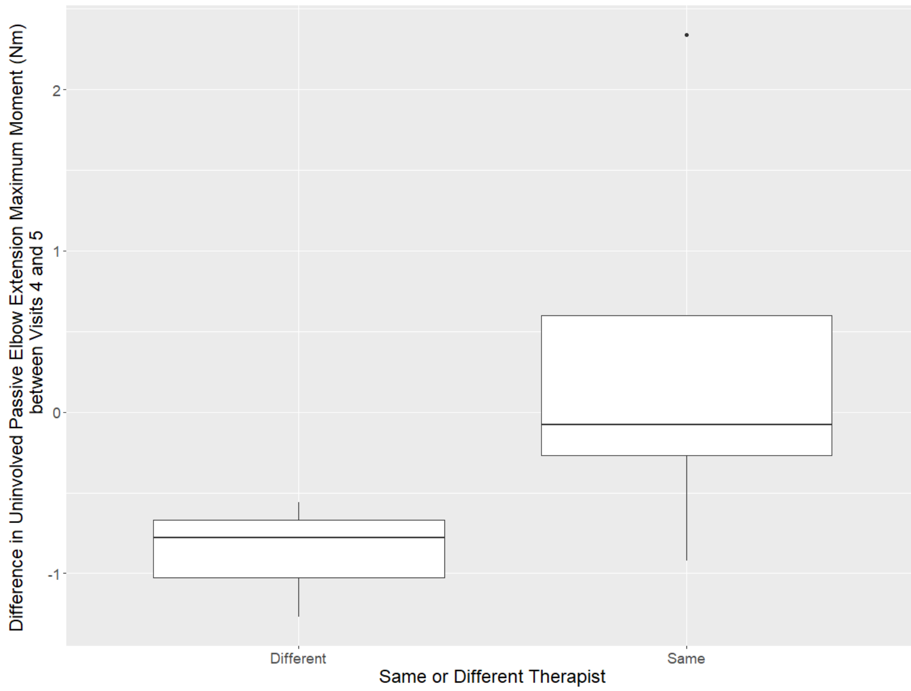

Figure 4.10 Mean change in uninvolved passive elbow extension therapist, applied Maximum torque between Visit 4 and Visit 5
Different: -0.870, Same: 0.334, p=0.0988

CHAPTER 5. CONCLUSION/DISCUSSION

5.1 Conclusion

This study indicates that the maximum torque applied during elbow end ROM testing is consistent between raters during the first round of testing, across both limbs, and in both tests of flexion and extension, and in later appointments torque used by different raters showed greater variation. The amount of torque used specifically by rater number one accounted for six of the seven differences noted in the pairwise comparisons. This could be because the rater's familiarity and experience with the test may have had an effect on the amount of torque applied to conduct each test. It was unexpected that those differences only manifested during the latter visits. This could be because the rater performing the test is more comfortable with the patient as they are further from the incident of injury and cast removal, therefore less precision or caution is used during later testing. Other confounding variables may exist because height, weight, age, and sex were not factored in these specific ANCOVA models, but to account for these variables, the number of participants needed would expand to a no longer feasible amount for the scope of this study.

When considering the results of a paired t-test of the involved and uninvolved limbs it is encouraging that individual raters showed no significant difference in maximum torque used between the involved and uninvolved limbs, because soundness of limb did not show a significant difference for any individual rater. Also, the variability introduced by rater using a dominant, or non-dominant hand or having to change positions depending on the side of the patient the test was being performed on, had no significant effect on the torque used during the test. This concluded that individual clinicians are consistent in ROM testing regardless of patients' soundness of limb.

It was found that there is no significant difference in the difference of maximum torque applied during consecutive appointments of either elbow flexion or extension end ROM tests, when the same or multiple raters were used during two consecutive appointments. A direct comparison between individual raters was not possible because combinations of first and second rater who conducted consecutive appointments were numerous; more tests would have to be conducted to make direct statistical comparisons between individual raters and different appointments. However, it is encouraging that when different raters perform ROM testing in subsequent visits, the amount of torque applied does not differ from that applied by one rater for both visits.

Overall, this appears to be a viable assessment protocol and can be used to analyze clinician applied maximum torque during elbow end ROM testing post-surgical repair. Future studies of this kind would require a large sample size to clarify results of this study, specifically those comparing rater reliability between two consecutive appointments involving the same participant.

5.2 Limitations

Because this study was performed in a clinical setting with children, appointment time length is considered. Placing the markers and performing all the tests related to this appointment is quite time-consuming. Having multiple clinicians perform these motion capture ROM tests and re-outfitting the markers for these measurements with an additional clinician was not possible. Therefore, a direct comparison from one rater to another at the same point in recovery is not possible.

Multiple participants were unable to or declined to attend all possible sessions. This limited the ability to conduct an interclass correlation coefficient test because of missing data points. A mixed statistical model was hence devised to make the maximum torque comparisons. Rater identity for each round of testing and time between rounds of testing was included as a covariant.

The statistical analysis does not allow solid conclusions between specific raters at different time points. If the protocol of this test were to be followed again, more passive elbow end ROM maximum torque measures would need to be collected, and more patients would need to be tested. If this was done it may be possible to isolate the effect of individual raters during each round of testing and measure their consistency in consecutive appointments as well as differences noted between any combination of raters in consecutive appointments. One simple metric that could be obtained is the standard deviation of the five individual tests that were taken during each visit as the mean clinical measure, variance measure for each clinician. A statistical analysis could then be performed between any two visits, in the same way, that this study does for a single visit

Because maximum torque is applied after end-feel is reached, it has little relation to the measured end ROM. A preliminary regression of elbow end ROM and maximum torque during flexion or extension was conducted and showed no relationship between measured end ROM and maximum applied torque. With more testing, each individual clinician could see if there is a relationship between the perceived limitation of the involved limb compared to the uninvolved limb. Again, more data would need to be collected to perform such a test.

In conjunction with this study minimum torque was also measured and found that the minimum torque applied to reach elbow end ROM had a mean of 2.6 Newton-meters (Eastman et al., 2022). This number of minimum end range torque may be more appropriate to analyze in conjunction with end ROM in flexion and extension because that is the necessary torque applied to reach end feel and end ROM, while max torque is what was applied to ensure end ROM was reached.

5.3 Discussion

This study is difficult to validate because it is the first of its kind and there are sources for error introduced by shoulder positioning, the compliance of individual patients to study protocols, inability to test multiple raters at the same appointment, and separate raters participating in the study. The effect of these sources of error are unknown but could be controlled for in later iterations of this study.

If this study were to be reproduced, positioning of the elbow is important. For this study the shoulder was positioned at 45 degrees of flexion and slightly abducted; elbow flexion and extension are usually measured with the shoulder at neutral position and down by the side. This could also have influenced the measured elbow range of motion because of the multi-joint nature of the biceps brachii and triceps. Additional factors affecting the torque measure of this study is that of gravity on the forearm during testing. A study that accounted for both factors might measure ROM with the shoulder at neutral, with the patient lying on their side to eliminate possible influence of gravity and bring the arm into a position more comparable to that on standard goniometric procedures. The specific position of this test was derived because marker visibility is necessary. With the patient on their side visibility of the medial epicondyle marker and medial wrist marker may not be visible when the arm is at the side. With this in mind the ROM test could be conducted with the palm facing the body so both the medial and lateral wrist markers are visible throughout the test. A marker set including virtual marker could be used to estimate the location of the medial epicondyle landmark.

End feel, and end ROM when the elbow is limited can be affected by passive structures such as ligament and joint capsule swelling, but also against muscle activity; for example, by conducting the same test with synchronized EMG of the biceps brachii during passive extension end ROM testing and the three heads of the triceps during passive flexion end ROM testing. Doing this could shed light on both the ROM limiting factor of the passive structures and the antagonist muscle groups.

A future study could be designed to measure the difference in maximum torque measured by multiple trained clinicians. Particularly, one clinician will apply the marker set for all patients and all the participating clinicians will be randomized and blinded. Each clinician will take end range of motion measurements with a multidimensional force transducer to measure maximumly applied torque for the whole group allowing for direct comparisons between participants. With this protocol, multiple shoulder positions could be considered for both elbow range of motion and maximum torque applied during the test. This accounts for marker placement variability that was present in this study and allows for examination of the effect of shoulder positioning on ROM and maximum applied torque.

To eliminate human error as much as possible, a computerized goniometer and programable piston outfitted on an elbow brace with an articulating joint would permit application of a consistent force throughout the entire ROM. In addition, a minimum and maximum value of torque to reach elbow end range flexion and extension can be established for the studied demographic at prescribed positions.

APPENDIX

APPENDIX: CALIBRATION OF STRAIN GAUGE

AMTI
FORCE AND MOTION

176 Waltham St. Watertown MA 02472
1-617-926-6700

Certificate of Calibration

AMTI Model: **HE2.5D-50**
Serial Number: SN:1291-6

Sensor Nominal Capacities:

Fx:	25 lbs
Fy:	25 lbs
Fz:	50 lbs

This calibration is certified to be traceable to the United States National Instutite of Standards & Technology (NIST) and to be in accordance with AMTI standard practice. The following instruments were used:

S-beam type load cell: Revere Model 9363-B10-250-20T1-R, SN 70355973, NIST traceable calibration 07 JUNE 2017 CAL-1084
Strain gage amplifier: AMTI Model MSA-6, SN 8080, AMTI calibration 18 MAY 2017 CAL-1195
DAQ Device: National Instruments Model USB-6215 (16-bit), SN E5F580, NIST traceable calibration 08 MAY 2017 CAL-1174

Lab Environment: 22° C 48%RH

Calibrated By: P. Aragon, Calibration Engineer Date: 31-Aug-2017

Certified By: Alan Walsh, Engineering Manager Date: 31-Aug-2017

Zero Offsets: (Relative to 2.5VDC)			Sensitivities:		
Fx	0.616	V	Fx	21.728	lb/V
Fy	-0.370	V	Fy	22.435	lb/V
Fz	-0.056	V	Fz	57.808	lb/V

Calibration Matrix [B]*			
	Fx[V]	Fy[V]	Fz[V]
Fx[lb]	21.728	0.301	-1.224
Fy[lb]	0.136	22.435	0.698
Fz[lb]	0.338	1.100	57.808

* [F] = [B] x [V]

$$N = (V + 0.056) * 257.14$$

(12/28/17)*

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