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Elbow Patients' Data Collection and Analysis: An Examination of Electromyography Healing Patterns

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Abstract

Musculoskeletal conditions are the most common cause of severe long-term pain and physical disability, accounting for the highest disability costs of about $17 billion yearly. To provide better rehabilitation tactics, the knowledge gap between injuries and their healing mechanisms needs to be addressed. The use of electromyography (EMG) is very popular in detecting neuromuscular diseases or nerve lesions; however, there is limited knowledge available for quantifying healing patterns of EMG in orthopedic patients who have injured their joints, muscles, or bones. In order to quantify the progress of orthopedic patients and assess their neuromuscular health and muscle synergy patterns, EMG signals were collected from 16 healthy individuals and 15 injured patients as they underwent rehabilitation. Subjects performed a series of standard motions such as flexion–extension of elbow and pronation–supination of the arm. Different metrics were used to process and analyze the EMG data collected using MATLAB. The metrics were as follows: root mean square, average rectified signal, mean spike amplitude, zero crossings, median power frequency, and mean power frequency. A normal range across the muscle groups has been identified and to which the patient population was compared. This comparison showed statistically significant differences in the magnitudes of muscle recruitment and activation between the two groups. Furthermore, a comparison within the patient population at the beginning of their therapy versus at the end of the therapy was conducted. Statistical differences arose in this second analysis, further proving that patients' signals tend to change and showing trends closer to those of the healthy population. The time domain metrics showed the greatest significant differences between the groups, specifically the root mean square and average rectified signal. This analysis was successful in showing a general trend of increased mean in the patient population compared to healthy individuals. The frequency domain metrics did not show statistical significance. The work presented successfully used several EMG metrics in order to distinguish an injured person from a healthy person and to determine if an injured patient is healing. Additionally, a database of EMG signals to be fed into the control system of the mechatronics

rehabilitative brace was created. This work has advanced the use of EMG beyond the scope of nerve damage. The experiments conducted showed that EMG could be used as method to assess musculoskeletal health.

Keywords

Smart Devices, Rehabilitation, Electromyography, EMG, Elbow, Upper, Limb, Arm

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Nomenclature and Acronyms

Acronyms

AAROM	Active Assisted Range of Motion
AROM	Active Range of Motion
AP	Action Potential
BB	Biceps Brachii
CNS	Central Nervous System
DOF	Degrees of Freedom
ECU	Extensor Carpi Ulnaris
EFE	Elbow Flexion–Extension Motion
EMG	Electromyography
FCU	Flexor Carpi Ulnaris
HOC	Hand Open–Close Motion
IMHA	Institute of Musculoskeletal Health and Arthritis
IMU	Inertial Measurement Unit
MSA	Mean Spike Amplitude
MSK	Musculoskeletal
MU	Motor Unit
MUAP	Motor Unit Action Potential
N	Number of Subjects

PROM	Passive Range of Motion
PS	Pronation–Supination Motion
PT	Pronator Teres
Rep	Repetition
RMS	Root Mean Square
ROM	Range of Motion
SE	Standard Error
SD	Standard Deviation
TB	Triceps Brachii
URD	Ulnar–Radial Deviation Motion
WFE	Wrist Flexion–Extension Motion

Units

Hz	Hertz
N	Newton
M	Meter
m/s	Meter/second
mV	Millivolts
g	Gram
N	Newton
H	Hours
s	Second

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Chapter 1

1 Introduction

Musculoskeletal (MSK) disorders and injuries are one of the leading causes of pain and disability in Canada. In 2013, upper limb injuries accounted for 12.1% of claims of lost time in Canada [1]. In addition to the long-term chronic nature of these conditions, they also exert a significant psychological toll on the patient and their families. People suffering from these conditions can live for decades with these painful debilitating conditions, which are in need of revolutionary rehabilitation strategies [2]. Moreover, the pain caused by the conditions may lead to physical inactivity, which is a precursor for numerous long-term health concerns that cause a cascade of further conditions and diseases that the individual has to endure.

MSK injuries that are related to sports, falls, or accidents cost the Canadian economy $15 billion each year [2]. The direct costs of these MSK conditions, such as hospital visits, physician visits, and drug prescriptions, are only one quarter of the overall costs. The remaining three quarters are attributed to indirect costs, which include underperformance in work, absence from work, etc. In the year 2000, the economic burden of MSK diseases was the 5th highest at $7.2 billion in Canada. A 2010 Canadian study showed that 11 million Canadians over the age of 12 are affected by MSK conditions yearly [3]. Additionally, it is predicted that the number of people with MSK conditions will increase from 11 million in 2007 to 15 million in 2031.

As a result of the huge burden of these conditions, the Canadian Institute of Musculoskeletal Health and Arthritis (IMHA) developed a strategic 5-year plan from 2014 to 2018, which includes the establishment of innovative approaches for tackling big research questions to effectively address the significant socio-economic burden caused by them. The IMHA strategic plan has a focus on the prevention of chronic musculoskeletal conditions through identifying and managing common risk factors, improving health, reducing injury, managing disability in the workplace, and reducing musculoskeletal disparities in vulnerable populations based on ethnicity, gender, age and geography. In an effort to contribute to decreasing the economic burden, better rehabilitation strategies are required.

1.1 Motivation

There is a growing interest in the interaction and interfacing of humans with robots as a new rehabilitation technique. The scientific and medical communities have been extensively doing research in the field of Rehabilitation Robotics as it is envisioned to restore mobility and functionally assist individuals who suffer from physical disabilities and disorders [4]. Therapies that rely on robotics have the potential to provide longer and more frequent treatment sessions as they can be done at home without the therapist. Additionally, they can deliver a higher degree of objectivity and repeatability than manual therapy. Moreover, they can overcome barriers of travel for frequent visits to the therapist, thereby increasing compliance.

As the field of Rehabilitation Robotics is growing, extensive research to advance in the field is required, especially on exoskeletons. Exoskeletons are wearable mechatronic systems in which the physical interface allows for an immediate transfer of mechanical power and exchange of information. In rehabilitation applications, exoskeletons can be designed to replicate movements performed with a therapist during treatment. Moreover, sensors attached to the exoskeleton can assess the forces and movements of the wearer thus providing the therapist with quantitative feedback on the progress of the patient throughout their rehabilitation process [5]. In addition to improving rehabilitation techniques, the developmental advances of exoskeletons can make them capable of assisting the wearer when performing certain motions. Signals collected from the sensors are fed into the device, and in return, the exoskeleton will be able to provide the mechanical power to carry out the task [4]. In other words, exoskeletons would be able to amplify the performance of the wearer and provide functional compensation.

The greater part of the information available on rehabilitation robots focuses on neurorehabilitation [6]. Some of these devices are driven by electromyography (EMG) sensor where the person is assisted with the motion according to the signals emitted. In contrast, very little research has been found on robotic therapy for orthopedic rehabilitation. This is where the CNS is intact and the limb has physical damage. Research shows that trauma or surgery may lead to disorders in the motor framework and mechanisms of compensation for adaptive functions [6]. Through the use of the emerging EMG technology, objective findings and information can be collected to aid in the assessment of functional movement tasks so that muscle imbalances can be

examined and ultimately lead to the improvement of therapy methods. In order to quantify the progress of the patient and assess neuromuscular health and muscle activation patterns, further research on EMG signals must be conducted on orthopedic patients. Since this is a fairly new and growing field, there is limited knowledge available that quantifies EMG in patients with no direct nerve lesions. The information collected can then be placed into a database that is used by the control system of a rehabilitation robotic device. The control system can draw additional information from the signal patterns that quantify health and optimal function, tailoring the therapy to each individual according to their current MSK health.

Further research on how to develop these control systems to perform smart decisions based on each patient's status of injury is needed, in order to provide individualized therapy.

1.2 General Problem Statement

Ideally, upper limb exoskeletons would be able understand and interpret the intended motion of the wearer, regardless of their injury level. Additionally, they would be able to assess the musculoskeletal level of health and provide the proper rehabilitation exercises accordingly. However, there is currently not enough information on EMG as a way to quantify muscle health. Health care providers pay a lot more attention to aspects that they can see using imaging techniques, such as broken bones and joint degeneration, whereas muscle function is generally never investigated.

In order to shift towards evidence-based practice in therapeutic modalities and provide proper individualized care, EMG research outside of the nerve conduction studies field is required. Emerging evidence proves that musculoskeletal injuries, trauma, and surgery can compromise muscle functions causing proprioceptive deficits that affect neuromuscular control [7]. The assessment of muscle as a diagnostic tool and an outcome measure of rehabilitation along with the creation of a database of signals to be fed into the control system is required for an exoskeleton to function properly. This will allow for a shift to the innovative paradigm for evaluating muscle energy which unlocks an entire new domain of data and information [8].

1.3 Research Objectives and Scope

The main goal of this thesis is to identify and classify patterns of muscle activation through the characterization of EMG signals in order to distinguish an injured person from a healthy person and to determine if an injured patient is healing. This will be done in a healthy control group and in patients solely with orthopedic trauma where their CNS is intact but the limb is damaged. This can be either a broken bone, a tear in the muscle, or damage to the joint itself. There is limited literature regarding an exact exercise prescription in this area therefore further research is needed.

To achieve this objective, the work has focused on the following objectives:

- To collect EMG data from healthy subjects and patients with musculoskeletal injuries
- To generate and analyze muscle recruitment EMG metrics of healthy subjects
- To generate, analyze, and compare EMG metrics of patients with musculoskeletal injuries to the healthy control group.
- To examine the recovering EMG patterns as the patients go through a full rehabilitation process
- To establish levels or phases of healing in attribution to the EMG signals
- To establish a database encompassing various EMG metrics necessary for the control system of a smart wearable device to assess the current level of healing of the wearer.

1.4 Overview of the Thesis

The structure of the rest of the thesis is as follows:

Chapter 2	Literature Review: Summarizes anatomy, physiology, MSK injuries, biomechanics of elbow, EMG signals structure, factors affecting EMG, principles of rehabilitation and modalities of therapy, and current state of the art exoskeletons
Chapter 3	Methods of Data Collection: Outlines the methods for collection of EMG signals. This includes the pilot study, instruments used, the protocol, and the iterations made. Methods of Signal Pre-Processing and Processing: Describes the process of extracting the important information from the signals such as application of filters for noise removal and calculating the linear envelope. Additionally, all the EMG based metrics used in both the time and frequency domain are discussed
Chapter 4	Results and Discussion: An in-depth analysis and comparison between the healthy group and the patient group is discussed as well as the patients at the first month of their therapy versus those at 4 or more months of their therapy.
Chapter 5	Conclusions and Future Work: Highlights the contributions of this thesis and proposed suggestions.
Appendix A	Ethics Permission and Approvals, Consent Form, and Trial Form
Appendix B	MATLAB Code
Appendix C	Statistical Analyses Tables

Chapter 2

2 Literature Review and Background

In order to analyze muscle activity using EMG from the upper limb, the anatomy, physiology, injuries, and current postoperative motion rehabilitation techniques were reviewed. Additionally, the EMG signal structure and factors that affect it were investigated. This section presents a summary of the relevant literature, including the human body and how it functions, EMG signals and their relationships with the body, and principles of rehabilitation. An extensive literature search was carried out between the periods of October 2014 and June 2016 using Google Scholar, PubMed, and the library at Western University with a combination of the following keywords: elbow, injury, rehabilitation, electromyography, EMG, orthopedic, and analysis. The resulting list of papers and books from this search references was reviewed giving priority to papers and books published within the last 15 years. A total of 71 papers and books were included in the complied database.

Based on the relevant information found in these papers, the remainder of this chapter is organized as follows: Section 2.2 outlines anatomical terminology related to position and orientation for a good understanding of references to the body. Section 2.3 describes the anatomy of bones, the articulations of the elbow joint, the receptors and what happens to them when the joint is injured. Section 2.4 outlines and explains the muscles in the arm, the breakdown of the muscle, how the muscle contracts on a micro level, and how a normal muscle contracts versus an injured muscle. Section 2.5 discusses EMG signals and their relationship with force, velocity, and fatigue. Section 2.6 mentions the different limiting factors of EMG. Section 2.7 overviews the principles of rehabilitation and current modalities of therapy. Finally, Section 2.8 provides a brief review of the current rehabilitation robots available on the market and in the research field.

2.1 Anatomical Position and Orientation

Anatomical position is the description of the body in a particular stance in which the body is upright, facing forward. The lower limbs are directed forward and the upper limbs are to the body's side with palms facing forward (supinated) as shown in Figure 2.1. In accordance with this position, universal frames of reference have been established to describe specific areas of the body accordingly as in Table 2.1 and Figure 2.1. These terms will be used throughout this thesis to explain anatomical landmarks or areas of injuries.

Table 2.1 Anatomical position terms and their meanings

Term	Meaning
Superior	Above (towards the head)
Inferior	Below (away from the head)
Anterior	The front of the body
Posterior	The back of the body
Medial	Towards the midline of the body
Lateral	Away from the midline of the body
Proximal	Close to the centre of the body
Distal	Away from the centre of the body

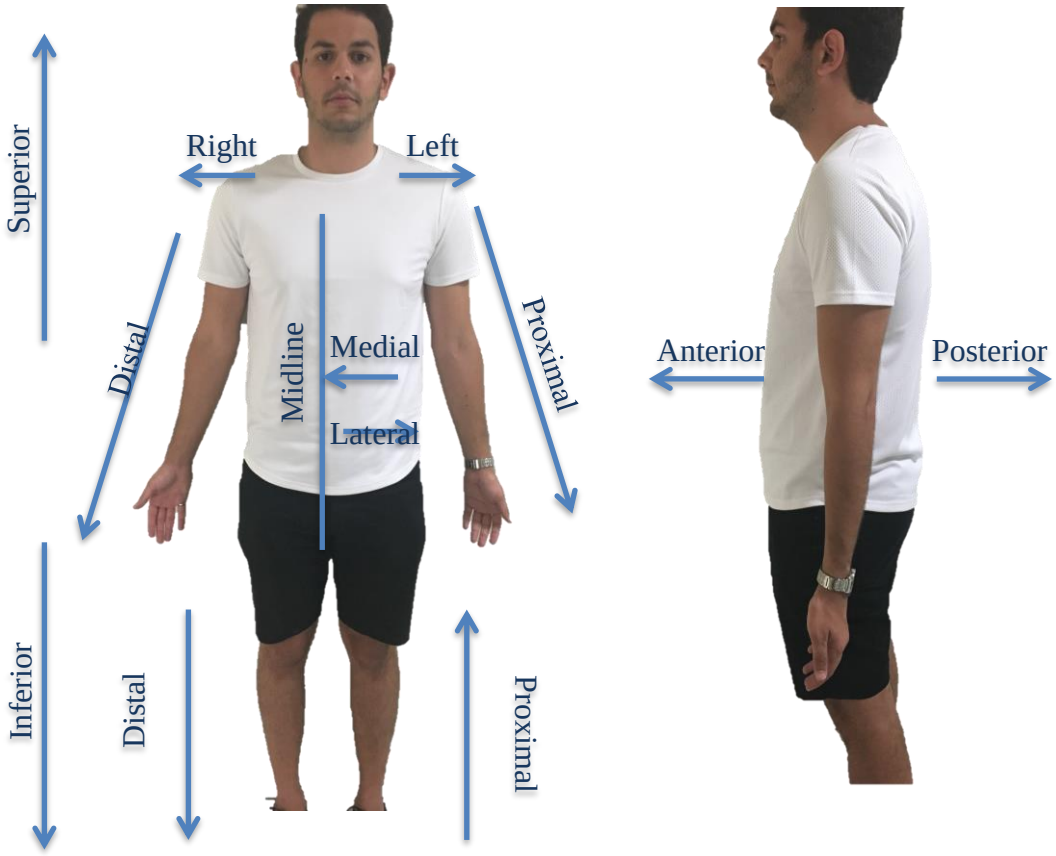


Figure 2.1. Anatomical position with reference terms

The wrist has three positions: Supine, neutral, and prone as shown in Figure 2.2:

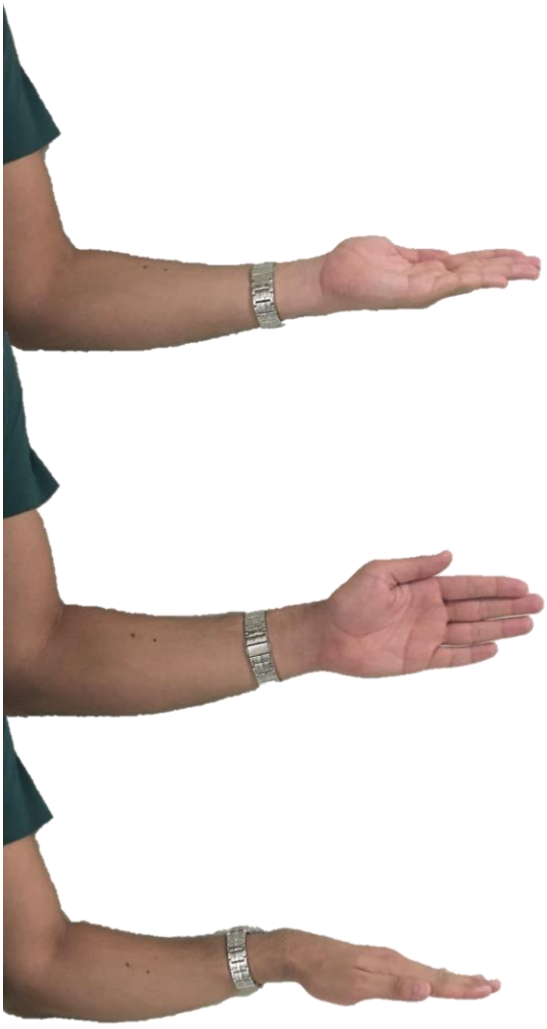


Figure 2.2. Positions of wrist: Supine (top), neutral (middle), and prone (bottom)

2.2 Osteology and Articulations

The elbow, a compound synovial joint in the centre of the arm, is one of the most commonly used joints in the body [9]. It is classified as trochoginglymoid joint possessing two degrees of freedom (DOF) [10][11]. A trochoid joint is a pivot joint that allows rotary motion while a ginglymoid joint is a hinge joint that allows a back and forth motion. However, there is a valgus–varus motion that occurs during elbow flexion of about 3 to 4 degrees [11]. In normal circumstances, the elbow flexion ranges from 0 or slightly hyperextended to about 150 degrees in flexion. As a result, this joint allows the arm to be more adaptable to multiple movements, yet is very prone to injury. It is a contact point of trauma and repetitive stress injuries. There are three main bones that make up the complex elbow joint: humerus, radius, and ulna as shown in Figures 2.3 and 2.4.

Distal Humerus:

The humerus is the sole bone in the upper arm as well as the largest in the entire arm. The humerus motion initiates various arm motions such as lifting, carrying, writing, and throwing. Muscles that move the upper arm and the forearm are attached to the humerus. For purposes of this thesis, the focus will be on the muscles that move the forearm; shoulder motions are excluded. Approaching the elbow joint, the humerus widens in a gradual manner while doubling in width. At the end of the humerus, towards the elbow joint, also referred to as the distal end, there are two joint-forming processes known as the capitulum and the trochlea [12].

Ulnohumeral Joint [11] [12]:

Medially, the trochlea interlocks with the ulna of the forearm to form the first articulation of the elbow joint: the humeroulnar joint. This joint resembles a simple uniaxial hinge movement allowing the ulna to angle with respect to the humerus. The trochlea is asymmetrical, with its axis of motion pointing superolateral to inferomedial. This allows for full range of motion using joint play. As a result, the carrying angle of the elbow is formed when the arms are at the side of the body. This angle is 10–15 degrees in men and 20–25 degrees in women.

Radiohumeral Joint [11] [12]:

Posteriorly, there is a small cavity in the humerus called the olecranon fossa in which the tip of the ulna, called the olecranon, locks into the humerus preventing further extension of the elbow beyond 180 degrees. On the lateral side of the arm, a convex shaped process in the humerus called the capitulum articulates with the concave shaped head of the radius in the forearm creating the second contact of the elbow joint called the humeroradial joint. This joint allows the forearm to passively rotate.

Proximal Radioulnar Joint [11] [12]:

The head of the radius interacts with the radial notch in the ulna making the proximal radioulnar joint. This joint allows the forearm to pronate and supinate.

Distal Radioulnar Joint [11] [12]:

Distally, the radius and ulna anchor to form the distal radioulnar joint. This joint is critical in forearm rotation.

Middle Radioulnar Joint [11] [12]:

Between the shafts of the radius and ulna lays the interosseous membrane and the oblique cord forming a syndesmosis, a slightly moveable joint. This area is affected by injury and immobilization of the elbow; as a result, the mechanics of the elbow can be affected when this area is injured. The soft tissue between the bones provides resistance to distal displacement of the radius during pulling movements, stabilizes the elbow by resisting proximal displacement of the radius on the ulna during pushing, provides stability to the other radioulnar joints, and transmits forces from the hand and the distal end of radius to the ulna.

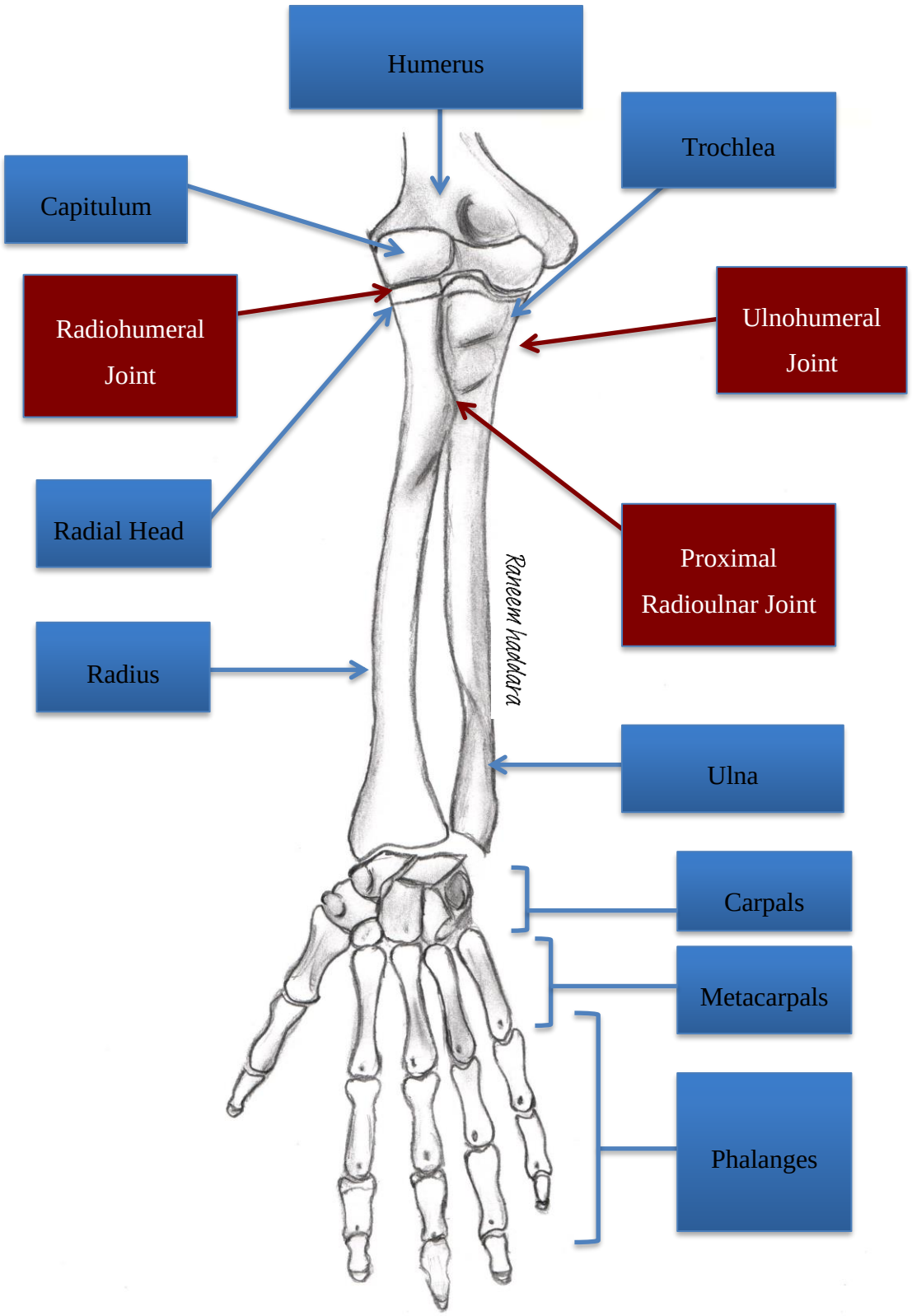


Figure 2.3. Anterior view of the arm bones and articulations

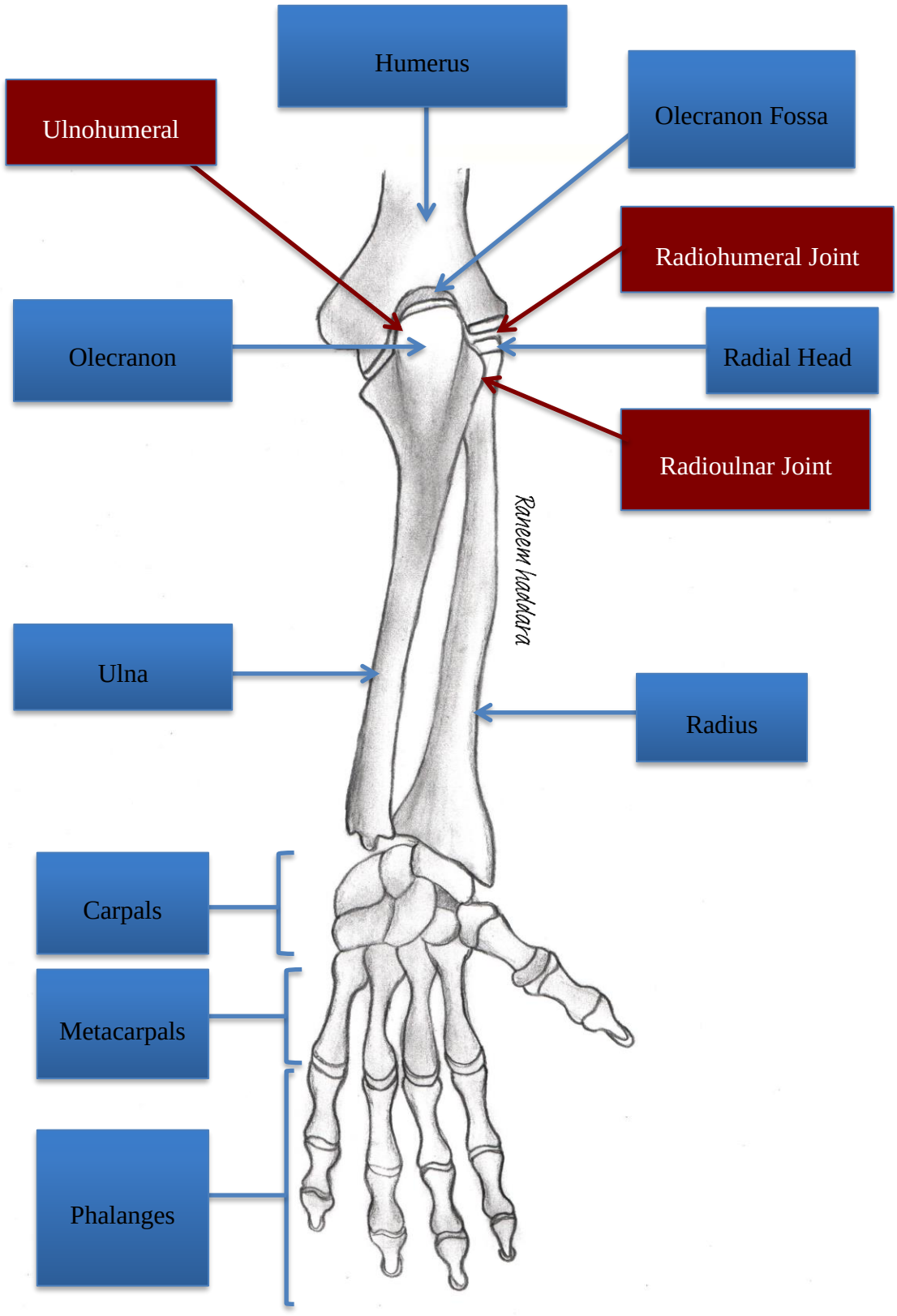


Figure 2.4. Posterior view of the arm bones and articulations

2.2.1 Acute Traumatic Injuries of Bone and Ligaments

MSK disorders and injuries of the elbow may occur in muscles that move the elbow, bones, tendons, cartilages, ligaments, and the joint capsule [1]. The elbow is the second most commonly dislocated joint in adults and the first most common in children [13]. These fractures are most commonly prevalent in contact sports such as football and wrestling or from falls. Hyperextension of the elbow, falling on the outstretched hand, or a combination of supination, valgus, and external rotation of the forearm during axial loading can all cause elbow dislocations [14]. The structures that are affected by the dislocation vary according to the impact and the individual. Ligaments, muscles, tendons, and bones can all be involved and injured by trauma.

Radial head fractures are the most common fractures in the elbow [15]. The mechanism of injury is very similar to that of the dislocations previously mentioned. Generally, stable fractures and dislocations can be managed conservatively with casting or bracing while complicated fractures require surgery [16].

Trauma to the elbow may affect intrinsic and/or extrinsic structures. Intrinsic structures include bone, joint capsule, and ligament while extrinsic structures are skin, nerves, tendons, and muscles [17]. The long-term consequences of these fractures or dislocations include loss of range of motion, loss or decrease in force production, instability of the joint, and chronic pain.

2.2.2 Receptors

Joint receptors convey information to the CNS about the position of the joint. This information is then interpreted by the CNS, which uses it to coordinate muscle activity about the joint in a stable manner [12]. This is achieved by determining a balance between the synergistic and antagonistic muscular forces. Additionally, the CNS guides the motion away from the pathologic ROM, in other words, the CNS protects the joint from performing motions that are unsafe.

Muscle spindles monitor the outcome of gravity acting upon a person and adjust the muscle tone in order for the person to be balanced [8]. If the muscle tone is too high or too low, the timing and effort of the motion is thrown off balance. Goodwin *et al*. conducted an experiment proving that signals from the muscle spindles produce the

sensation of limb movement [18]. Gandevia and Proske argued that muscle spindles are responsible for the sense of position and movement, tendon organs are responsible for tension, the sense of effort is generated within the CNS, and sense of balance is by the vestibular system[19][20][21].

There are a few nerves that innervate the muscles crossing the elbow joint. Their receptors detect changes in position, tension, compression, speed, muscle length, and force. When a change occurs, it is relayed to the CNS. According to the signals received by the CNS, integrated signals are then sent to modify the activations of motor units (MUs) to generate the suitable muscle tension for the desired motion [22]. Following elbow injury or trauma, this system may be compromised. Moreover, immobilization or limited mobility also causes abnormal programming of the receptor system function [22][23].

2.2.3 Proprioception and Neuromuscular Control

Proprioception contributes to the “motor programming” of neuromuscular control needed for motion, muscle reflex, and dynamic joint stability [24]. Lephart *et al*. argued that the neuromuscular feedback mechanism is compromised with injury and abnormalities. As a result of the proprioceptive deficits, the individual becomes more susceptible to re-injury and enters a relentless cascade of re-injury and functional instability as shown in Figure 2.5.

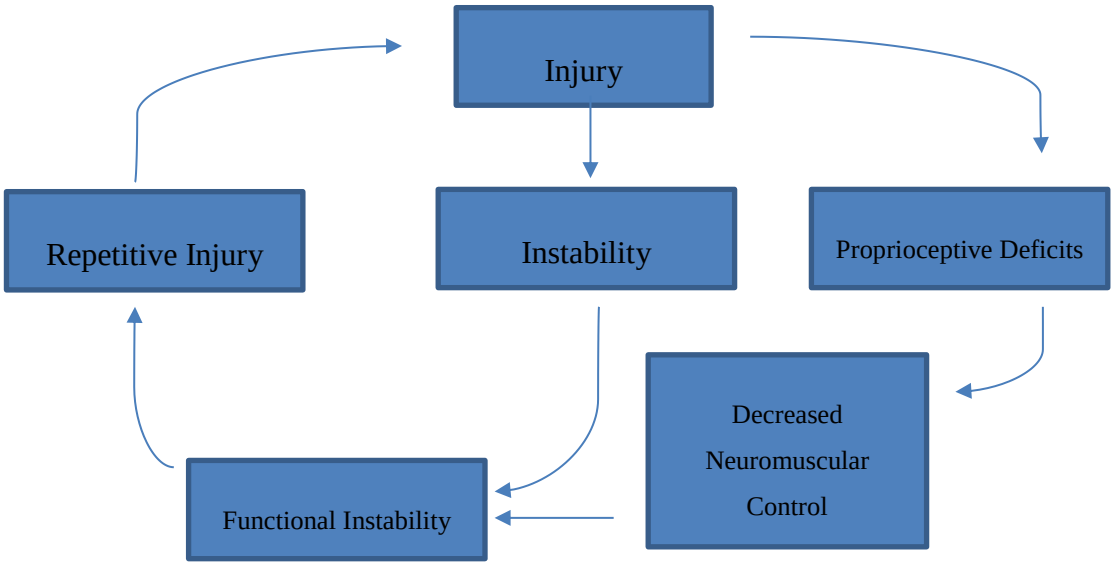


Figure 2.5. Cascade of injury

A study by Wyke showed a patient that depicted changes in posture after an injury to the ankle capsule despite a complete recovery [25]. Normal strength and range of motion was restored with no pain. However, the patient complained of the ankle "giving away". This proves that due to the injury, the neural input to the CNS (see Figure 2.6) was compromised resulting in a decrease in neuromuscular control [24]. Consequently, in addition to pain-free range of motion and regaining strength, the retrieval of neuromuscular control is crucial in order for the patient to function optimally in a normal manner. Figure 2.6 reiterates that if any of the mechanoreceptors are compromised, the CNS will no longer relay proper information to the motor control and thus results in incorrect muscle activation.

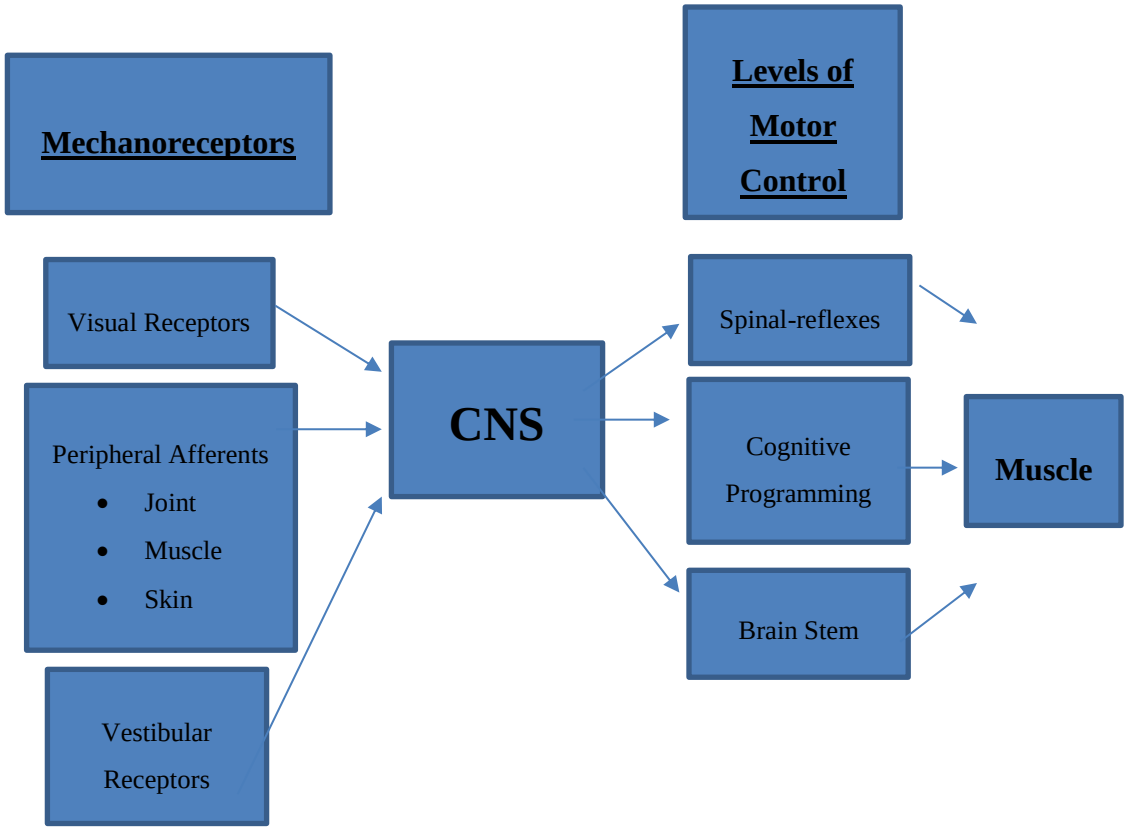


Figure 2.6 Effect of Injuries on CNS and Muscle Control

2.3 Muscle Anatomy and Physiology of the Upper Limb

To understand the mechanisms of injury and rehabilitation, a full understanding of the muscles involved in this mechanism is crucial. The next section will include an explanation of muscle anatomy such as the origin and insertion of the muscles. Additionally, a description of how movement is produced on a macro and micro level is conducted.

2.3.1 Muscles of Interest

The muscles that were explored in this thesis are mentioned in Table 2.2. The table mentions the muscle group each muscle belongs to along with the origin, insertion, and function of the muscle.

Table 2.2. A list of the muscles of interest, their origins, insertions, and their function [11]

Muscle	**Muscle Group**	**Origin**	**Insertion**	**Function**
Biceps Brachii	Elbow Flexor and Supinator	Coracoid Process of Scapula and Supraglenoid Tubercle	Radial Tuberosity and bicipital aponeurosis	Major Flexor and Strong Supinator
Extensor Carpi Ulnaris	Elbow Flexor and Wrist Extensor	Supracondylar Bony Column	Dorsal base of second metacarpal	Primarily a wrist extensor, however its orientation suggests it might function as an elbow flexor in pronation
Pronator Teres	Elbow Flexor and Pronator	Medial Supracondylar Ridge of Humerus and Coronoid Process of Ulna	Middle of the Lateral Surface of Radius	Strong Pronator of Arm and Weak Elbow Flexor

Flexor Carpi Ulnaris	Elbow Flexor and Pronator	Medial Epicondyle and Medial Margin on Olecranon of Ulna	Pisiform (Carpal)	Wrist Flexor, Ulnar Deviator, and Weak Elbow Extensor
Triceps Brachii	Elbow Extensor	Infraglenoid Tubercle, Proximal Lateral Intramuscular Septum on Posterior Surface of Humerus, and Distal half of the Posteromedial Surface of the Humerus	Olecranon Process of Ulna	Primary Elbow Extensor

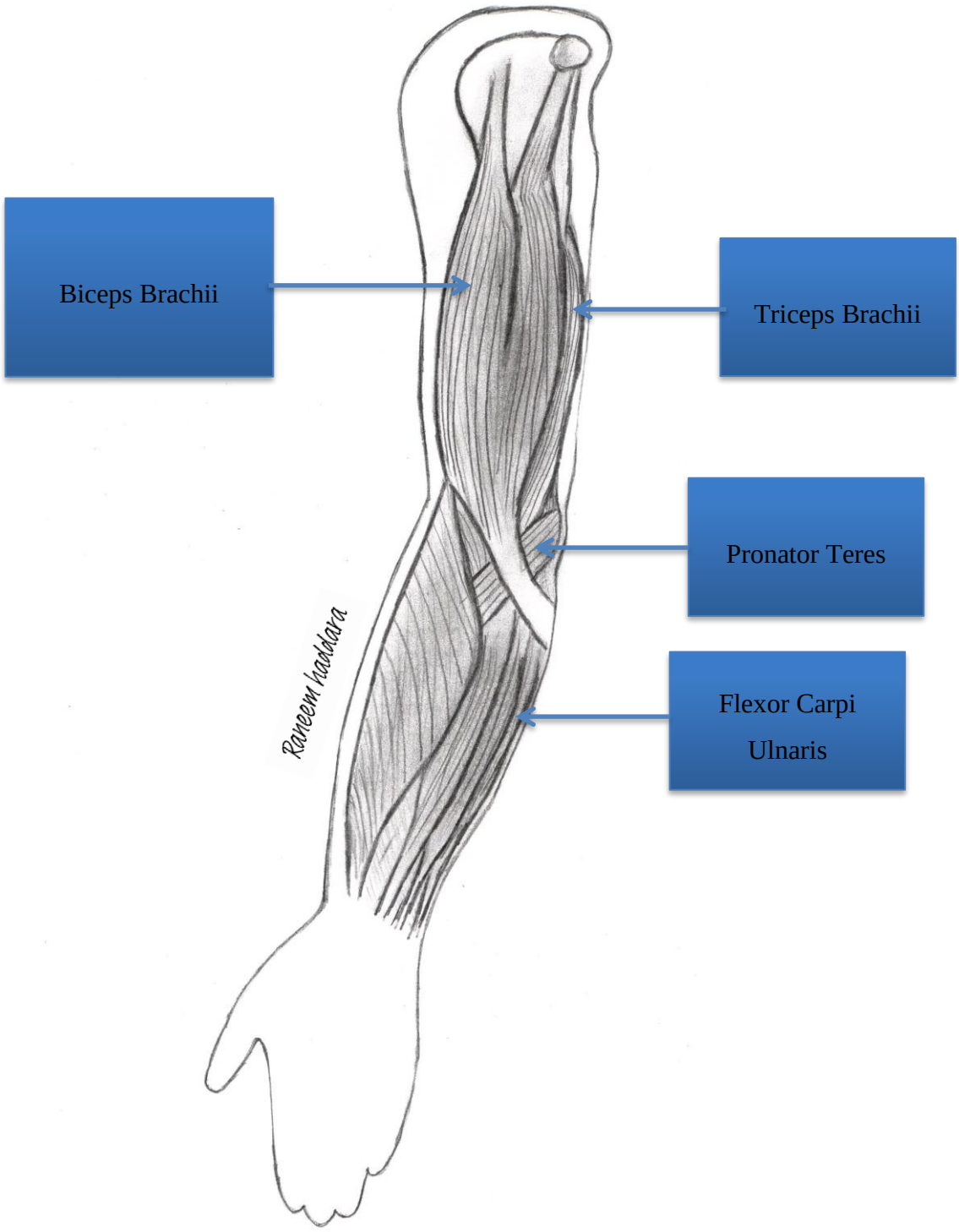


Figure 2.7. Anterior arm muscles

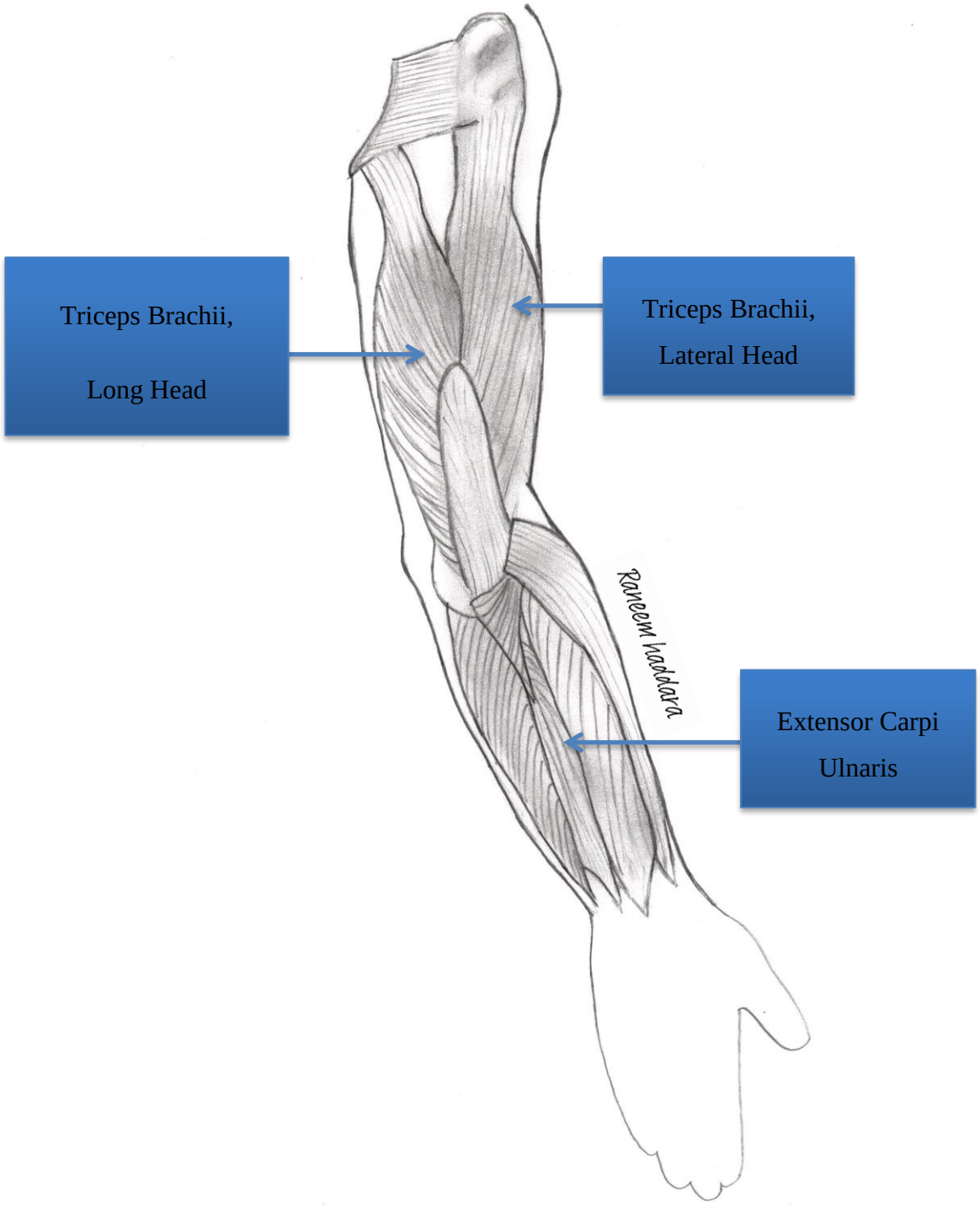


Figure 2.8. Posterior muscles of arm

2.3.2 Muscle Fibre

Macroscopically, muscle fibres are grouped together and are identified by their line of action, origins and insertions, and direction of pull. However, on a deeper level, one muscle can be broken down to several compartments (fascicles) with fibres running in the same direction or a different one. Each of these muscle fibre-containing compartments can be further broken down into clusters of individual fibres called myofibrils. Each myofibril contains myosin (thick fibres) and actin filaments (thin fibres), which make the basic single unit anatomical structure of a muscle called the sarcomere (see Figures 2.10 and 2.11). During an action potential propagation, the filaments slide on top of each other forming myosin-actin cross bridges causing the muscle contraction. The maximum strength is obtained in the middle range where the most amount of bridges are formed.

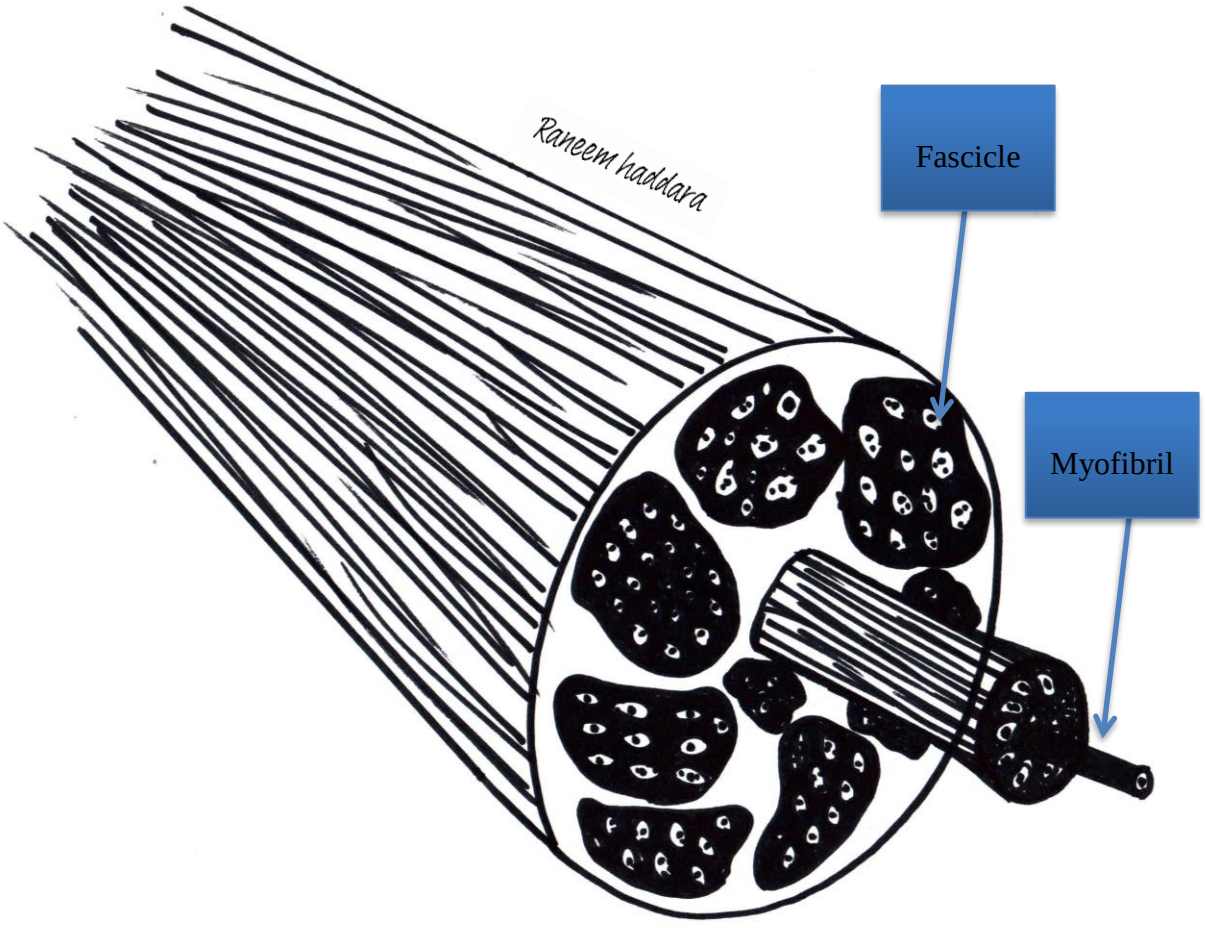


Figure 2.9. Breakdown of skeletal muscle showing the fascicles and myofibrils

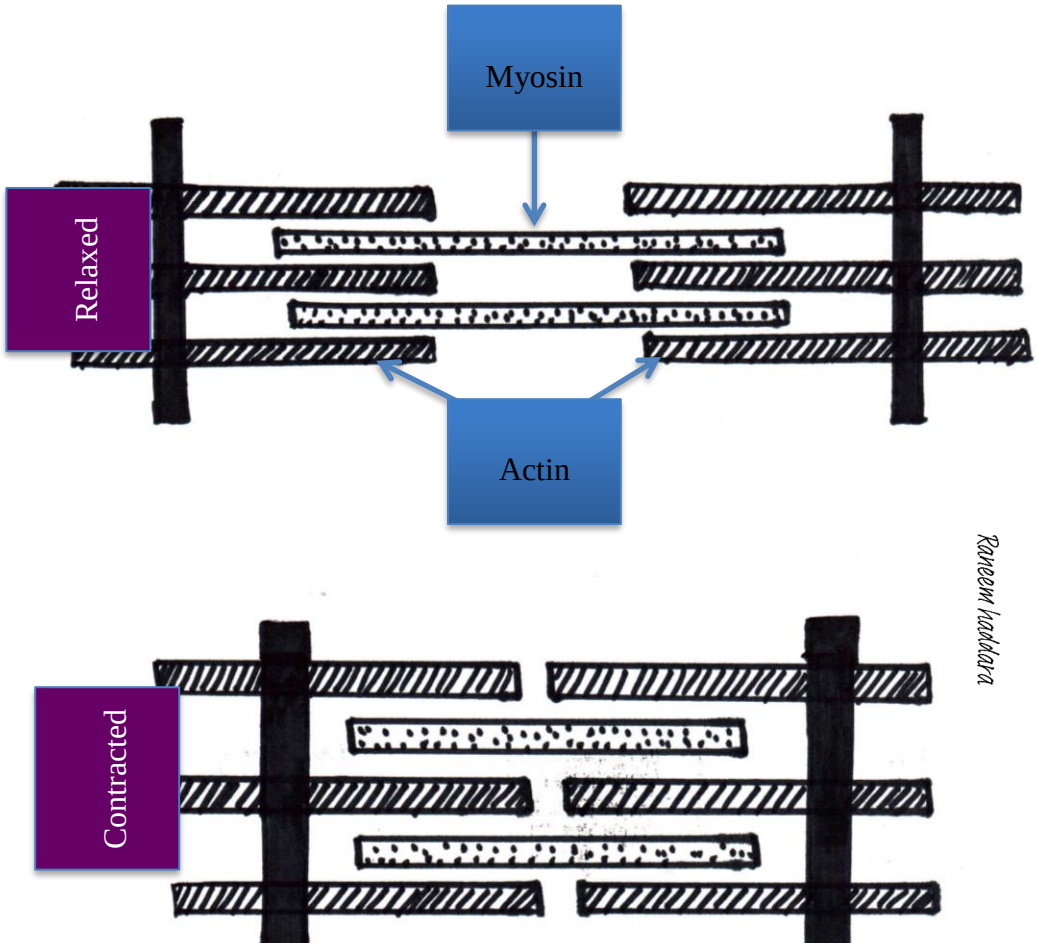


Figure 2.10. The positions of actin and myosin during a relaxed and contracted muscle

2.3.3 Motor Units and Action Potentials

As described in Section 2.4.2, a muscle is comprised of bundles of cells specialized for contraction and relaxation [26]. The main function of these specialized cells is to generate forces and motions. The contraction of skeletal muscle is commenced by voluntary impulses in the neurons to the muscle. Each bundle of these fibres is innervated by a single motor neuron, called a Motor Unit (MU) as shown in Figure 2.12 below [27].

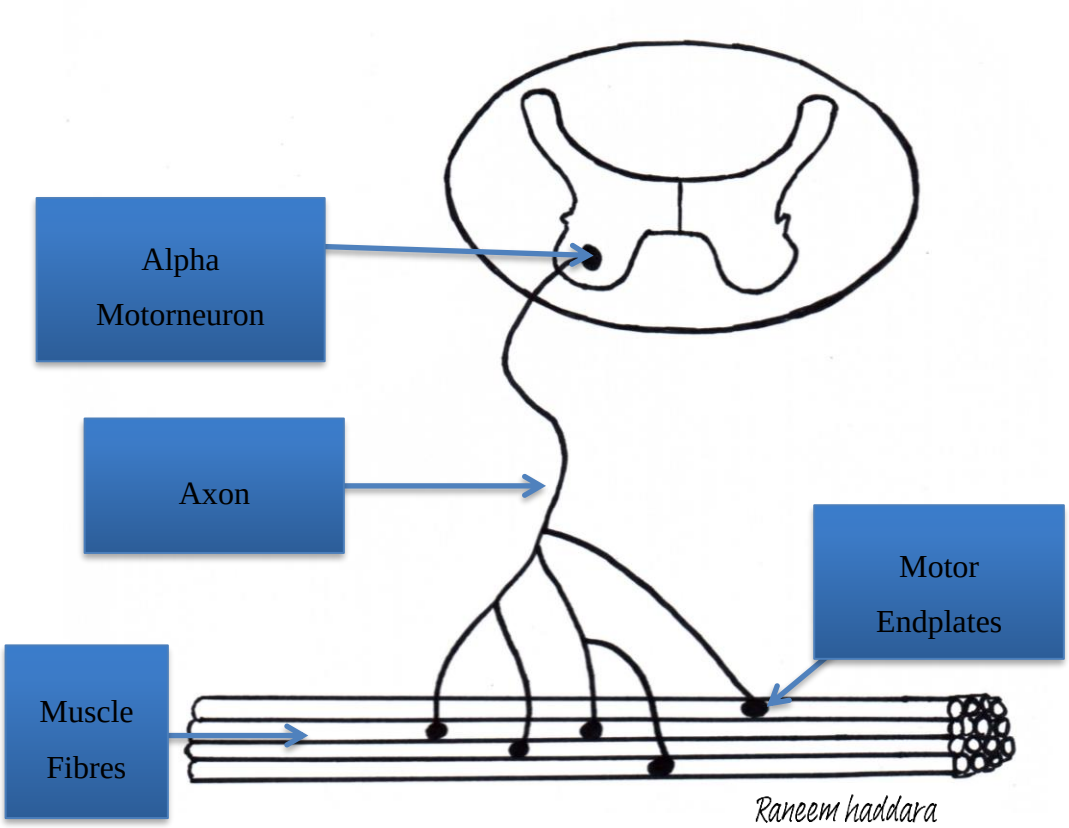
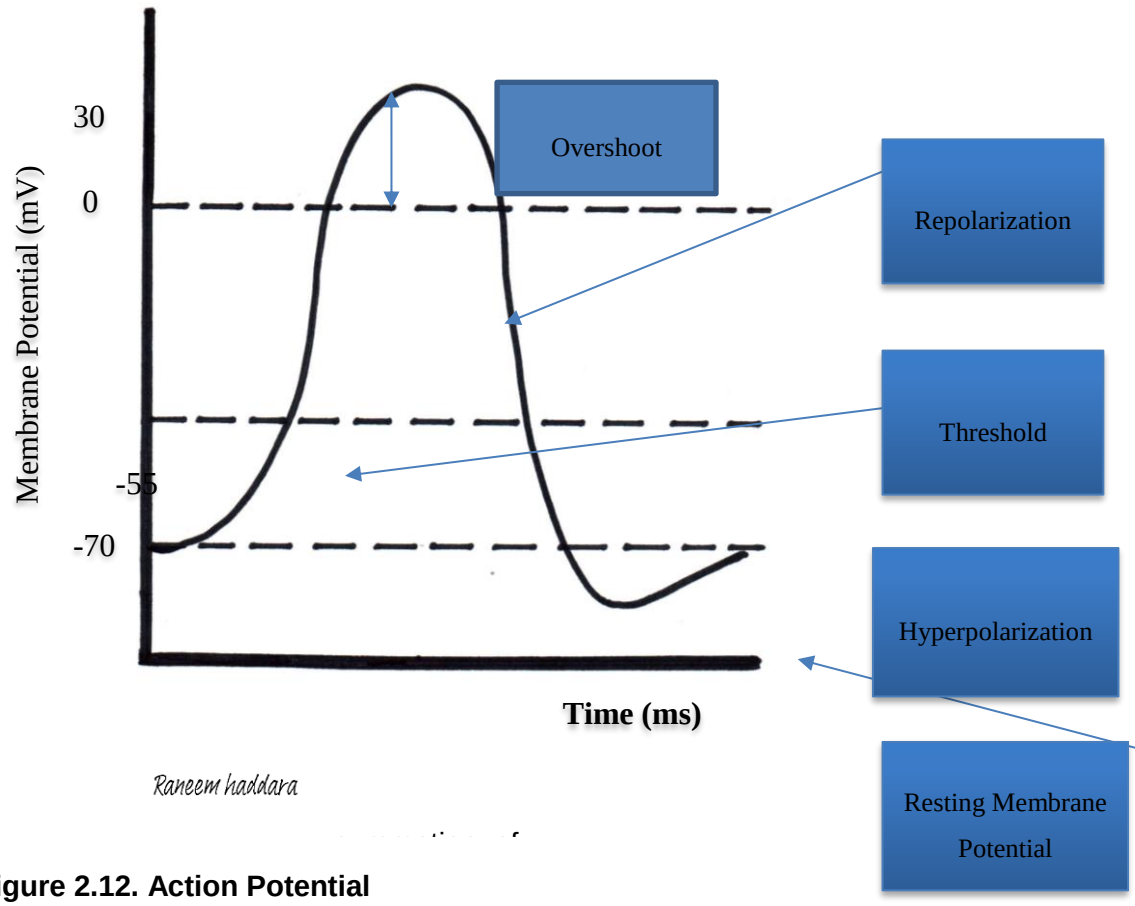


Figure 2.11. Motor unit

A MU is the smallest neurological functional unit that controls muscles in contraction and relaxation. Muscle fibre contraction occurs when the action potential reaching the motor neuron and axon terminal surpasses the threshold of depolarization (Figure 2.13) [28]. This initiates a propagation of action potentials along the length of the muscle fibre causing tension. At rest, the α-motor neuron becomes inactive causing relaxation of the muscle fibres. A single muscle fibre receives input from only one MU [29]. During contraction of a muscle, the smallest fibres are recruited first [8]. As the exertion increases, the larger fibres and MUs are then employed. Normally, the firing rate is between 8 and 50 Hz. As the demand increases, the firing rate increases to higher frequencies. Additionally, as the demand increases, a shift towards a synchronous pattern of activation occurs. Asynchronous patterns are what provide a smooth movement.



The

mus**Figure 2.12. Action Potential**

MU is called a Motor Unit Action Potential (MUAP) [26]. MUAPs can be measured by surface EMG electrodes. These are “little microphones which listen for MUAPs” [30] .

These electrodes measure the voltage of the summation of the active MUs depolarizing and repolarizing during the movement (see Figures 2.14 and 2.15).

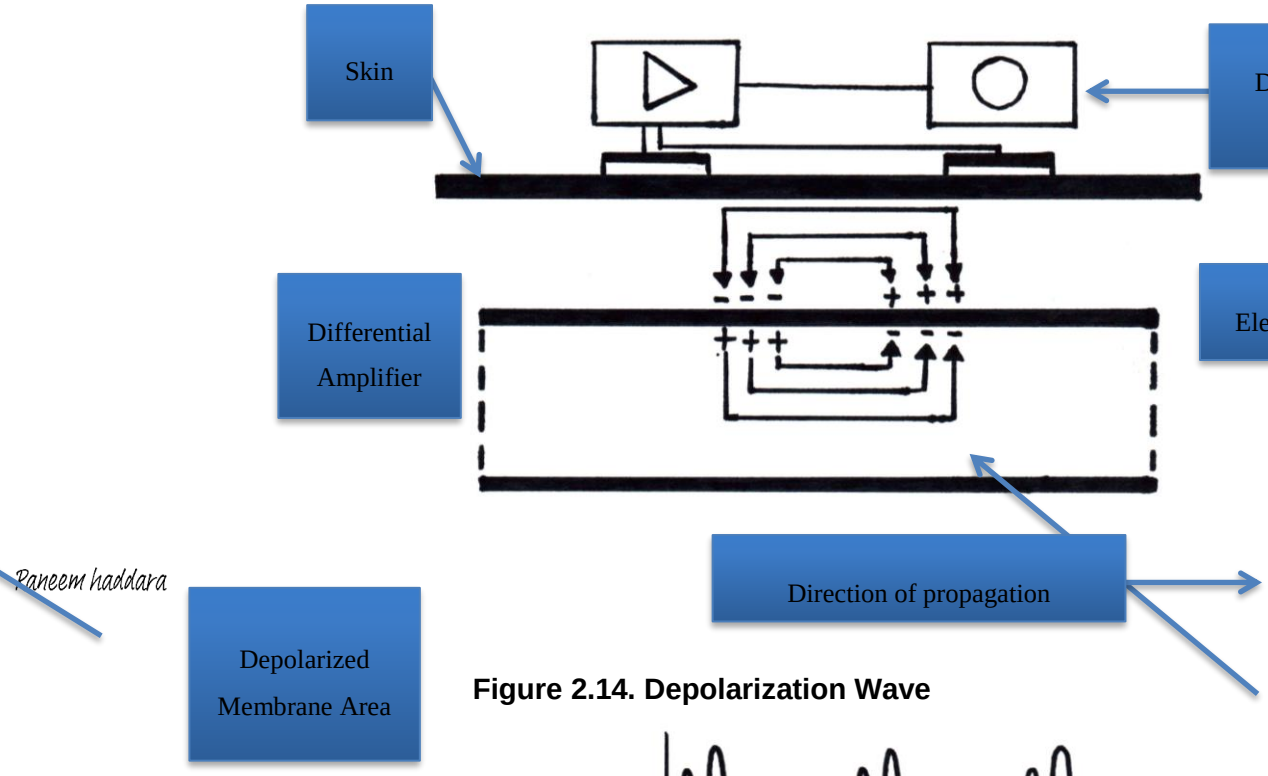


Figure 2.14. Depolarization Wave

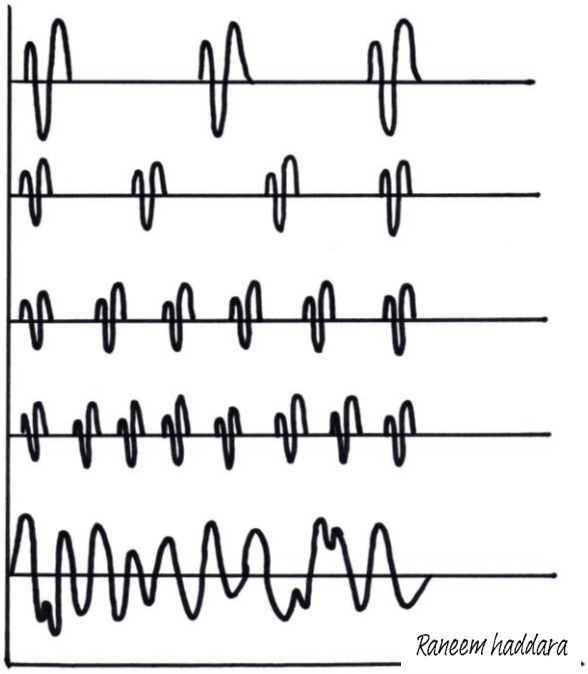


Figure 2.13. Superimposition of MU Recruitment

2.3.4 Types of Contraction

After explaining how muscles contract on a micro level, it is important to note what type of contractions this organ system can produce. There are four types of muscle contractions [8]. The first type of contraction is *concentric*. This occurs when a muscle shortens during a contraction and has enough force to overcome the external resistance. An example of this contraction is during elbow flexion while lifting a dumbbell. The biceps shortens during flexion overcoming the resistance of the weight being carried. Next there is *eccentric,* which occurs when a muscle lengthens during a contraction of an already shortened muscle and the external force is greater than the tension in the muscle. An example of this is when a person carrying a dumbbell extends his or her arm to achieve elbow extension. The person's biceps lengthens as the weight forces the elbow in the direction of extension. There is a special class of contraction that is a subset of both concentric and eccentric called *isotonic*. This occurs during either concentric or eccentric contractions however the muscle force being generated is constant throughout. Lastly, *isometric* contraction occurs when the muscle length remains constant during a contraction. Isometric contraction can be achieved through any static exercise such as holding a pushup halfway through.

2.3.5 Biomechanics and Kinetic Chain of the Elbow

Muscles are the active elements of the body acting upon static elements, i.e., our bones, to produce movement. According to the origin and insertion of each muscle, its contraction and relaxation can contribute significantly or minimally to move a joint. Forces and moments created at the elbow are stabilized by a series of structures such as the muscles, tendons, ligaments, and articular surfaces [11]. Similarly, the magnitude and direction of forces in the elbow along with the muscle tension is dependent on the external loading conditions and the muscle response. In order to calculate these forces produced by muscles about the elbow joint, a two-dimensional force analysis through a free-body analysis is required. The following set of equilibrium equations were displayed in an analysis by Morrey [11]:

$$\sum |F_i| f_{xi} + R_x + P_x = 0$$

$$\sum |F_i| f_{yi} + R_y + P_y = 0$$

$$\sum |F_i| . r_i + P + r_p = 0$$

where $|F_i|$ is the magnitude of the tension in the muscle *i*; f_{xi} and f_{yi} are components in the *x* and *y* directions for the unit vector alongside the line of action of muscle; R_x and R_y are the *x* and *y* components of the joint contact force; P, P_x, and P_y are the magnitudes of the applied forces on the forearm and its associated components; and r_i and r_p are the moment arms of the muscle force and the applied force to the elbow joint centre, respectively.

Table 2.3 provides a summary of the forces produced and the lines of actions by muscles of interest around the elbow joint to allow for flexion and extension of the elbow. As shown, the biceps and Triceps provide the majority of the force contributions while the forearm muscles provide limited to no contribution according to the calculations. Nevertheless, their anatomical positions suggest that they do provide contributions but are inconsistently reported in literature.

Elbow Joint Flexion Angle (degree)		***0°***			***30°***		
Muscle	PCSA	Moment Arm (r*)	F_x	F_y	Moment Arm (r)	F_x	F_y
BB	4.6	20.7	0.86	0.5	20.7	.86	.5
FCU	1.6	0	1	0.04	0	.99	0.04
ECU	1.7	-0.2	.99	.16	-9.0	.99	.16
TB	18.8	-23.0	1.0	0.09	-26.0	.81	.59
Elbow Joint Flexion Angle (degree)		***90°***			***120°***		
Muscle	PCSA	Moment Arm (r)	F_x	F_y	Moment Arm (r)	F_x	F_y
BB	4.6	45.5	.17	.99	0	1	.04
FCU	1.6	0	1	0.04	-8.0	.98	.19
ECU	1.7	-9.0	.98	.19	-17.0	0.05	1.0
TB	18.8	-20.0	.05	1.0	40	.35	.93
r* = mm, Physiologic Cross-Sectional Area (PCSA) = cm^2							

Table 2.3. Physiological cross-sectional area, unit force vector, and moment arm of elbow muscles in sagittal plane

2.3.6 Muscle Coactivation and Recruitment Pattern

Muscle tone is the state of constant low-level contraction that is shown by the muscles at rest [29]. This is crucial in order to stabilize the entire skeleton and maintain the joint positions, providing a basis for resistance to gravity and movement. If the MUs are all continuously firing, the body will become exhausted very quickly; therefore the body smoothly rotates contractions throughout the various MUs to maintain a constant resting contraction throughout. This is referred to as an asynchronous contraction pattern. Emotional stress and anxiety can affect this resting muscle tone. When motions are executed they are superimposed upon the resting muscle tone. If the muscle tone is higher or lower than normal levels, the timing of actions becomes distorted.

Muscle coactivation is the activation of agonist and antagonist muscle groups simultaneously around a joint [31]. It is a common strategy to control voluntary motion while moderating the impedance of the joint to stabilize it [32]. A study by Glousman *et al*. depicted changes in kinematics through the use of EMG in baseball pitchers with shoulder instability [33]. A reduction in neuromuscular activation was observed in the muscles of the chest and back which provided anterior stability to the shoulder. As a result, a compensatory over-activation of muscles in the arm was discovered in an attempt to provide the shoulder with anterior stability. The loss in healthy synchronized patterns of muscle activation has been attributed to the altered kinematics and proprioception resulting in continuous microtrauma. Similarly, evidence also suggests reduced activity of the forearm flexor and pronator muscles and increased activity of the extensor muscles with ulnar collateral ligament injuries in baseball players [34].

2.3.7 Normal vs. Compromised Function

An understanding of normal functioning movement is important to health care professionals such as physicians and therapists. Normal function is defined as the ability of the body to move and interact within its environment [7]. Panjabi introduced a concept of integrated systems in describing spinal function [35]. He discussed that the normal function requires a chain of systems functioning together. The “control system” which is the CNS of the body is the first component of this integrated system followed by the “active elements” which are the muscles and the “passive elements” which are the vertebrae and discs. He then argued that if any of these “systems” were to malfunction, it could lead to one of the following responses:

1- A compensatory immediate response from the other functional systems

2- A long-term adaptive response of the other systems

3- An injury to one or more of the other systems

In the first response, function would be compromised in comparison to the second response, which would appear normal, however the mechanism of stabilization would be different. In the third and last response, an obvious dysfunction would be depicted in the form of pain and limited ROM. Since our understanding of the “control system” is limited, extensive research is required to understand the mechanics of movement in both active and passive perspectives [7].

2.4 EMG Signals

Biomedical signals are a collection of electrical signals obtained from physiological activities of living organisms. They can be acquired from a wide range of activities starting from protein and genetic sequences, to neural and cardiac rhythms, and finally to tissue and organ images [36]. These signals are usually a function of time and can be quantified through their amplitude, frequency, and phase [30]. By processing these signals, health care professionals can detect and monitor specific illnesses or diseases.

Since the nervous system is responsible in controlling the muscle activity of the body, the EMG signal demonstrates the electrical currents of the area being measured during muscle contraction thus providing data describing muscular morphology and neuromuscular activity [27]. As a result, the analysis and interpretation of EMG signals is crucial in the field of management and rehabilitation of motor disabilities and musculoskeletal injuries.

2.4.1 EMG Signals Assessment

Dynamic Surface EMG is the assessment of how muscular energy is used to provide support against gravity, how it executes movements, and how it rests. Through EMG assessment, one can look at the timing of muscle firing, i.e., if it fires early or late in the recruitment pattern. Moreover, looking at if a particular motion is activating the muscle that it is intended to or if there is a substitution in the pattern. In addition to looking at muscle dysfunction within a motion, it is important to note how previous baseline levels

affect the movements and how the motions might disrupt the capacity to return to resting levels.

When health care providers examine muscles, they routinely perform muscle testing where they isolate the strength of a given muscle. The practitioner needs to position the limb in an abnormal position in order to separate the strength of the muscle of interest. These tests do not follow natural movement patterns since they are “slices of a unique movement pattern, taken out of a normal muscle contraction context and frozen in time” [8]. As a result, manual tests are not a good representation of the health or damage of the muscle function. They are only pertinent to the degree that the information obtained can be placed within a more functional context.

The use of surface EMG objective findings can provide information to clinicians and researchers regarding the mechanisms of muscle function and dysfunction and consequently, improve therapy methods [8]. In addition to muscle testing, EMG can be used to monitor the muscles involved or suspected to be involved in a particular movement. Therefore, practitioners can evaluate not only muscle’s strength, but also their synergy with other muscles.

2.4.1.1 Baseline Level

The baseline level is a part of the signal can be an important marker for presenting muscle dysfunction prior to and following a motion. When the muscles are resting, the muscle tone should be minimal. However, with injuries, some individuals may have an elevated baseline signal indicating high muscle tone activity, or a disturbance in muscle spindles secondary to a trigger point [8]

2.4.1.2 Recovery of Baseline Level

Between repetitions of a motion and after the motion is completed, the resting tone should go back to the baseline level during the recovery period. If a muscle fails to return to pre-baseline levels, it is termed post-movement irritability. Failure to return to resting amplitude is a sign of disturbance in muscle spindles secondary to a trigger point [8][29].

2.4.2 EMG Signals and Clinical Syndromes

Atypical EMG signals may arise from different types of MSK dysfunctions. These dysfunctions are briefly explained below [8] [29]:

- Learned guarding or bracing: This causes heightened muscle activity in reaction to pain or discomfort upon motion.
- Learned inhibition/weakness: A decreased muscle activity in reaction to pain or discomfort upon motion is depicted
- Acute, reflexive spasm/inhibition: This can cause either an increase or decrease in muscle tension induced by pain or effusion.
- Peripheral weakness or deconditioning: Weakness or deconditioning causes impaired muscle activity due to disuse commonly caused after immobilization, surgery, or a very sedentary lifestyle and poor motor habits. It may result in muscle atrophy, ineffective vascularization, and compromised biochemical and physiological function. Symptoms may include a decrease in peak torque, power deficits, and fatigue. Maximal efforts will probably show decreased muscular activity while submaximal efforts will show increased activity.
- Compensation for joint hypomobility or hypermobility: Excessive laxity or stiffness may cause the neuromuscular system to compensate accordingly by over or under-activating specific muscles.
- Chronic faulty motor programs: The CNS learns to cope with muscle weakness, instability, trigger points, pain, and various other aspects of injury through the disruption normal muscle co-activation patterns (agonist-antagonist-synergist relationships).

2.4.3 EMG Amplitude and Force Relationship

Various pathologies can affect the EMG-Force relationship [37]. MUAPs amplitude cancellation, synergistic muscles, co-contractions, and passive elements contribute to the linearity of the EMG amplitude and force relationships. EMG models often simplify the relationship by assuming that it is linear [38]

When additional force is required, more MUs are activated [37]. MUs are activated by increasing size, starting with the smallest. This process of increasing the number of active MUs is called recruitment. The number of MUs recruited have an effect on the EMG signal; the larger the number of MUs are recruited, the larger the signal amplitude. Moreover, there is an alternative way of increasing muscular force. This can be achieved through increasing the rate of firing — the frequency of the MUs. This is referred to as firing rate and also has an effect on EMG signal amplitudes. The minimum firing rate is dependent on the muscle but it can range between 5 and 10 impulses per second. As the request for force increases, the firing rate increases up to a maximum firing rate surpassing 60 impulses per second in some muscles [39].

2.4.4 EMG and Force-Velocity Relationship

The velocity of a muscle contraction can affect the amount of force produced. The speed of a muscle contraction is dependent on the rate of cross-bridging at the sarcomere level [8]. Less force is produced when the contractions are faster.

2.4.5 EMG and Fatigue Relationship

When the muscle contraction is sustained for an extended period of time, the conduction velocities of the action potentials decrease and the muscle begins to discharge less frequently [29]. Muscle fatigue effects are related to insufficient blood flow to the tissue, the exhaustion of energy sources, and the accumulation of metabolites in the muscles. This accumulation of metabolites includes hydrogen ions, which ultimately slows down the MUAP. Moreover, a shift of dominance from fast-twitch to slow-twitch fibres may occur [8]. As a result, increased amplitude is often associated with fatigue due to the increased synchronization of the motor unit in maximal sustained contractions while motor units decrease in firing leading to smaller amplitudes of the submaximal contractions [37]. Finally, a reduction in median frequency of the signal power is exhibited with fatigue

As muscle fatigues, the frequency of the firing drops; however, the mean amplitude may stay the same. As a consequence, using the time domain alone as a fatigue indicator may be very difficult. A shift to the frequency domain is crucial where two important measures of muscle fatigue are examined: median and mean frequency. As

muscles fatigue, both mean and median frequencies decrease. However, these indicators have been primarily applied in isometric contractions [40].

2.5 Factors Affecting EMG Signals

It is important to note the limitations of the thesis. Surface EMG is an evolving field and there is a need for further advancements, as plentiful research remains undone. Factors affecting EMG signals are briefly discussed in this section.

2.5.1 EMG Noise

One of the most significant factors that affect the EMG signal is noise. Noise may arise from the imprecision of the equipment which cannot be eliminated, it can be reduced by using high quality electrodes [26]. Noise is also created from our own bodies, referred to as “ambient noise”, which is due to electromagnetic radiations emitted from the human body. This type of noise is also virtually impossible to avoid. Another source of noise is motion artifacts, which skew the data and cause irregularities. The electrode interface or electrode cable can cause this. Motion artifacts can be decreased by an appropriate design of the electronic circuitry and set-up.

2.5.2 Movement of Skin in Dynamic Motion

Another influencer of EMG signals is the sliding of skin on top of muscles. Recordings obtained in dynamic conditions are more problematic than in static conditions as the muscles change their resting length and move under the skin, as shown in Figure 2.16 on the next page. Consequently, the dominant muscle belly portion is selected as much as possible in order to prevent the electrodes from being away from the muscle during motions.

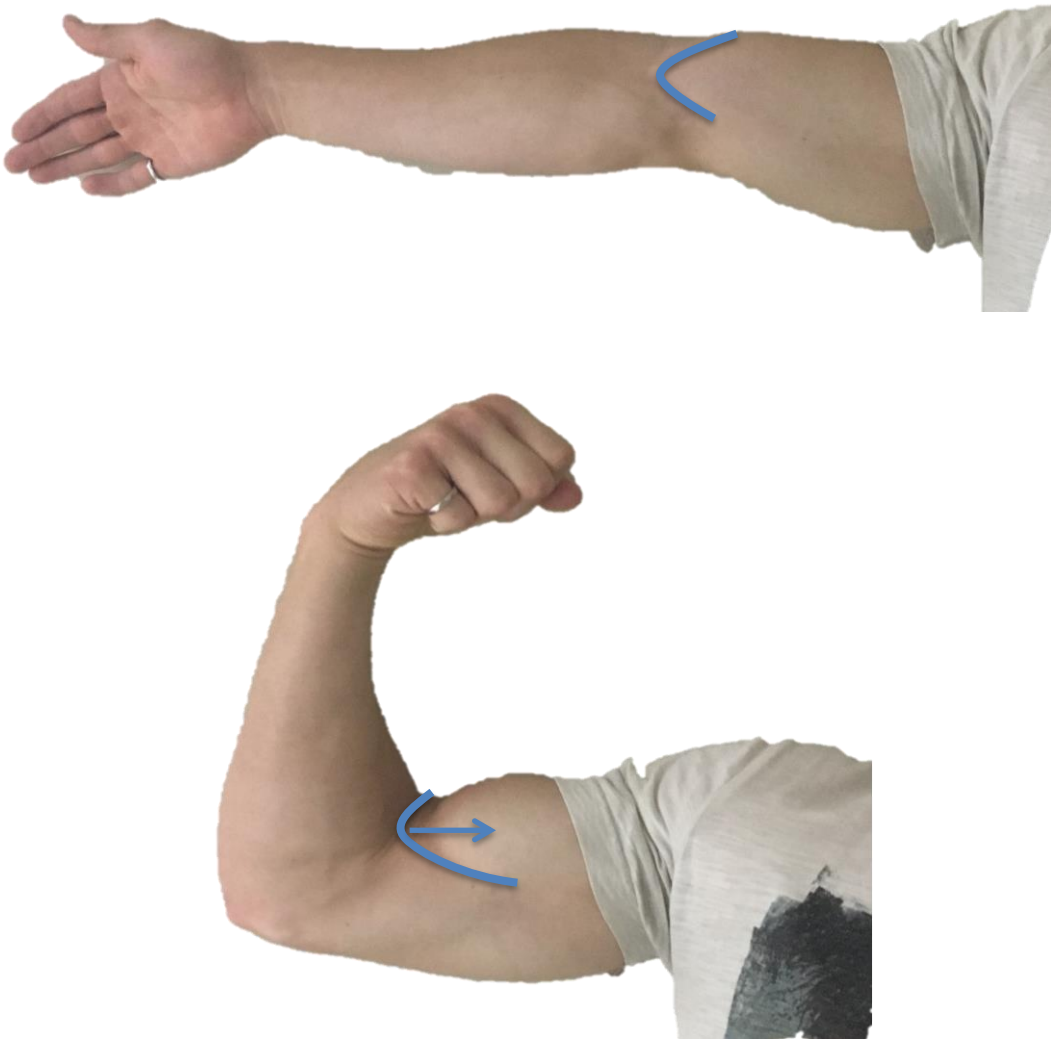


Figure 2.15. Biceps muscle shifting medially during flexion

2.5.3 Cross Talk

Muscle crosstalk also contributes to the contamination of pure EMG from the muscles of interest. Cross talk are signals picked up by the surface EMG electrodes produced by neighboring muscles to the one under investigation [40]. It is minimized by placing the electrodes on the middle of the muscle belly with an inter-electrode distance of 2 cm.

2.5.4 Causative Factors

In addition to the previously mentioned influencers, the following factors also have an elemental effect on the signal [41]:

Extrinsic Factors: These are those factors that are influenced by the experimental setup, and include the following:

- Electrode configuration:
  - Distance between electrodes [41]
  - Surface area of electrodes [41]
  - Shape of electrodes [41]
- Electrode placement in reference to:
  - Motor points [30]
  - Orientation of muscle fibres [30]
  - Lateral edge of the muscles [30]
- Electrical noise:
  - Inherent noise – general equipment noise [26][37]
  - Ambient noise – electromagnetic radiation [26]
  - Motion artifact – motion causing data skewing [42]
  - Power line noise [42] [37]
- Skin preparation and impedance [43]
- Perspiration
- Temperature [44] [45]

Intrinsic Factors: Includes all anatomical, physiological, and biochemical characteristics, such as the following:

- Number of active MUs [41]
- Fibre type composition [41]
- Blood flow [41]
- Muscle fibre diameter [41]
- Amount of tissue between electrode and muscle [41]
- Muscle and fibre length [46] [47]

2.5.5 Conclusions

Considering all the possible contaminating and limiting factors described, dynamic EMG recordings still provide a degree of consistency between the readings. Surface EMG allows for reliable [48], predictive, and descriptive information that is of high value for researchers and health care professionals.

2.6 General Principles of Rehabilitation of Elbow and Upper Arm

In order for the mechatronics brace to provide treatment to its wearer, an understanding of current rehabilitation protocols is required. There is a plethora of research in the rehabilitation field, however there are no set distinct literature guidelines or randomized clinical trials for elbow trauma patients [49]. Additionally, rehabilitation protocols are often inadequately described and therefore non reproducible. Health care professionals often depend on the methods and protocols they were trained to do by a senior health care provider and consequently they use their own subjective judgment to treat each patient.

2.6.1 Classification

The elbow and forearm are crucial parts of the upper body kinetic chain which executes the activities of daily living as well as activities of work, sports, and leisure [7]. In comparison with other fractures and injuries, the elbow has a higher complication rate and poorer outcomes with a trend to rapidly develop intra-articular and periarticular adhesions, which results in loss of motion [11] [17]. The goal of elbow rehabilitation is to restore optimal, pain-free function within the limitations of the patient, anatomically and physiologically. Functional restoration of the elbow joint is mainly achieved through exercise therapy. Initially, an assessment must be made to identify performance level and deficits or impairments in the motions [7]. In the follow up assessments, it is crucial to establish a phase of healing and the degree of severity of the condition in terms of neuromusculoskeletal and sensorimotor impairment. Early motion is desired to decrease or prevent the adhesions, mitigate against the effects of rigidity, assist the lymphatic system and venous return, and control pain though proprioceptive mechanisms[11]. These advantages must be compared to the risk of irritating healing tissues.

According to Morrey and Smith, the principles to guide the rehabilitation process are as follows: 1) establish a complete and accurate diagnosis; 2) control pain and inflammation; 3) implement early, atraumatic motion; 4) re-establish neuromuscular control about the elbow; 5) rehabilitate the elbow in the context of the kinetic chain.

Vicenzio *et al*. argued that therapy is broken down into 4 categories. 1) improvement of general aerobic fitness; 2) restoration of muscle length and ROM; 3) strength, endurance, and power improvements; 4) normalization of elbow and forearm coordination and proprioception [13].

Wilk *et al*. discussed the basic principles of rehabilitation and grouped them into four stages: 1) stage of early mobilization; 2) intermediate stage of recovery; 3) stage of advanced strengthening; and finally 4) stage of return to working/sports activity.

Currently, there are no randomized clinical trials or consensus on literature guidelines about elbow rehabilitation for traumatic pathologies [49]. Therapists are conducting a wide range of non-operative treatment regimens and rehabilitation programs. Traditionally, clinical techniques to assess muscle function are mechanically based to measure strength, endurance, and ROM [50]. Conversely, this form of mechanical testing has a major drawback: if the patient is able to over work other “systems” or aspects of his or her body to achieve the desired motion, the patient will appear fully recovered. These tests do no provide muscle-specific information; they simply group all the muscles that move a particular joint as one large muscle while overlooking any synergistic interactions as the muscles co-activate to achieve the motion [50] . Advanced imaging methods such as CTs and MRIs provide a more objective measure than the mechanical methods, but provide limited information on the dynamic muscle function. In contrast, EMG provides the required method to access the physiological properties of the muscles that causes them to generate force, produce motions, and execute activities of daily living [51].

2.7 Modalities of Therapy

In the clinical setting, there are numerous forms of therapy administered according to the subjective view of the therapist or health care practitioner. The most common forms of therapy are listed below [11] [12]:

1. Protection and Relative Rest: This is when the joint is immobilized to protect its healing tissues from further damage.
2. Ice: Placing ice on the injured area reduces inflammation, lessens pain, and controls muscle spasms.
3. Compression and Elevation: The placement of a compressive band along with elevation helps reduce swelling of the injured area.
4. Medications: Drugs are prescribed by the physician according to the patient's injury and symptoms.
5. Passive Range of Motion (PROM): This is the movement of the joint by an external force without the patient exerting any effort to produce movement. It is important to induce tissue length change to eventually gain motion after the injury.
6. Active Assisted Range of Motion (AAROM): AAROM is the movement of the joint initiated by the patient with external help to assist the full motion intended. This prevents intra-articular and peri-articular adhesions, controls edema, promotes cartilage healing, and modulates pain.
7. Active Range of Motion (AROM): This motion is fully performed by the patient with no external help like in AAROM. Movement of the joint achieves the same effects as AAROM with the addition of the stimulation of neuromuscular control
8. Resisted Range of Motion (RROM) [12] [11]: RROM occurs when an external force is resisting the motion produced by the patient, which helps in the restoration of neuromuscular control.

2.8 Exoskeleton Robots for Upper Limb Rehabilitation

Robotic neurorehabilitation is an attractive form of therapy as it is easy to implement can be applied to a broad assortment of motor impairment, and is greatly reliable. Rehabilitative exoskeletons currently available are aimed for neurorehabilitation of stroke, brachial plexus injuries, traumatic brain injuries, spinal cord injuries, and neurological disorders (multiple sclerosis, amytrophic lateral sclerosis) patients [52]. In comparison to manual therapy, exoskeletons can provide long intensive rehabilitation that are not dependent on the skills or fatigue levels of the therapist providing the treatment [53]. The therapist does not need to be present allowing for more frequent treatment eventually reducing cost. Virtual games can be implemented to provide a more

engaging exercise experience for the patients. In addition to the constant treatment, the exoskeletons can be used to quantitatively evaluate the patient and his or her progress through the measurement of physical parameters such as speed and strength of the movements [54]. Robotics in the rehabilitation field is gradually being recognized by the therapist community as being as a strong competitor, or even better than manual therapy.

There are a few commercially available upper arm rehabilitation devices and others that are not commercially available but that are relevant to this work. These have been summarized in Table 2.4.

Table 2.4. Arm rehabilitation devices with descriptions

Device	Description	DOF	Actuated/Passive	Portability	Assessment of Patient Progress
ArmeoPower	Full upper arm exoskeleton	6	Actuated	Not portable	Yes
ArmeoSpring	Elbow and shoulder passive exoskeleton	N/A	Passive	Not portable	Yes
ArmeoBoom	Full upper arm sling suspension system	N/A	Passive	Portable	No
MyoPro	Elbow and wrist myoelectric driven orthoses	4	Active	Portable	Yes
NEUROExos	Elbow exoskeleton	4	Active and passive	No	N/A
Wear-Me	EMG driven elbow exoskeleton	2	Active	Yes	No

In order for these exoskeletons to be controlled properly, advanced control systems are crucial. The control system must be able to use information coming from the sensors on the patient such as EMG, position, force, etc. and provide the support needed by the actuation system accordingly. Moreover, the control system is required to go through a decision making process according to the database of EMG signals available and the input from the sensors to provide the assistance at the right time and in the right direction regardless of health status or injury. In addition to the sensors' input, a therapist's input is also essential. After assessment of the patient, the therapist can program the brace to provide the correct therapy according to each patient's needs. These decisions include deciding on what sort of movements are safe and how many repetitions are required for optimal therapy. This is depicted in Figure 2.16.

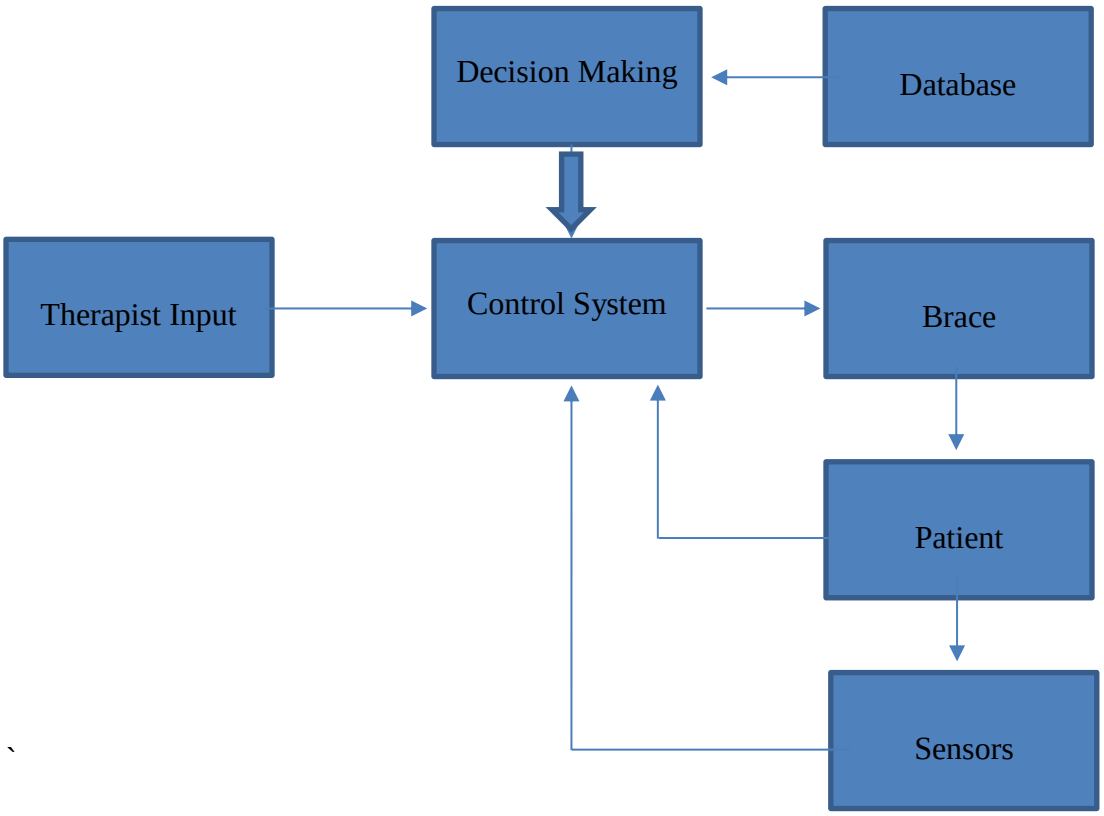


Figure 2.16. Control system inputs and outputs

In summary, this chapter reviewed the relevant anatomy and biomechanics of the upper limb in which the bones and muscles investigated were presented. In addition to the anatomy of the limb depicted on a macro level, the internal physiology of the muscle fibres and how they contract was explained. Following a firm understanding of muscle contraction, patterns of activation in normal and compromised functioning was discussed. EMG signals were then explained in terms of structure, relevance to health, and the factors that affect the signals. Finally, chapter 2 examined the current modalities of therapy in the rehab field in both the traditional hospital setting and the robotics field.

3 Signal Collection and Processing

The previous chapter outlined and explained all of the necessary information regarding the anatomy of the elbow and EMG signals, as background knowledge. Based on this, this chapter presents the work that was performed in order to quantify health using EMG signals. The following sections outline the materials, methods of data collection, and signal processing techniques that were implemented in order to meet the objectives of this thesis.

3.1 Materials and Specifications of Instruments Used

EMG signals were acquired by a Standard Electrophysiological Amplifier System with Signal Conditioning *(Model 2024F, Intronix Technologies Corporation, Bolton, Ontario, Canada)* running in parallel with a host personal computer equipped with Intronix Myoguide™ System *(Model 8008, Intronix Technologies Corporation, Bolton, Ontario, Canada)* for raw signal data acquisition. The signals recorded were converted from analog to digital with a 16-bit accuracy in the ±10 V range sampled at 4 kHz. Prior to sampling, the signals were analog low-pass filtered at 500 Hz and high-pass filtered at 10 Hz to remove noise and possible movement artifacts.

The following instruments and devices were used for the data collection:

1. Standard Mechanical Brace *(OSSUR®):* The OSSUR brace limits the motion of the wearer in ranges of 0° to 120° in flexion and 0° to 90° in extension. This brace was used to examine muscle signals within specific ranges of motion in the pilot study. An image of the brace is shown below in Figure 3.1.

Figure 3.1. OSSUR brace

2. Standard Electrophysiological Amplifier System with Signal Conditioning *(Intronix Model 2024F):* The Intronix Model 2024F provides EMG recording with a low impedance output of 10 Ohms. This device has 4 channels where two boxes are shown in Figure 3.2 on the right.

3. A standard NI DAQ NI9205: A National Instruments NI9205 32 channel ± 10V, 250kS/s 16 bit analog input module is used with the Standard Electrophysiological Amplifier System with Signal Conditioning "Intronix Model 2024F" for data recording and sending to a PC as displayed in Figure 3.2 on the far left.

Figure 3.2. Intronix Data Acquisition System

4. Standard Intronix Model 8008 *(Myoguide™ System):* The "Myoguide Software System is designed to amplify the EMG signals from muscles (see Figure 3.3).

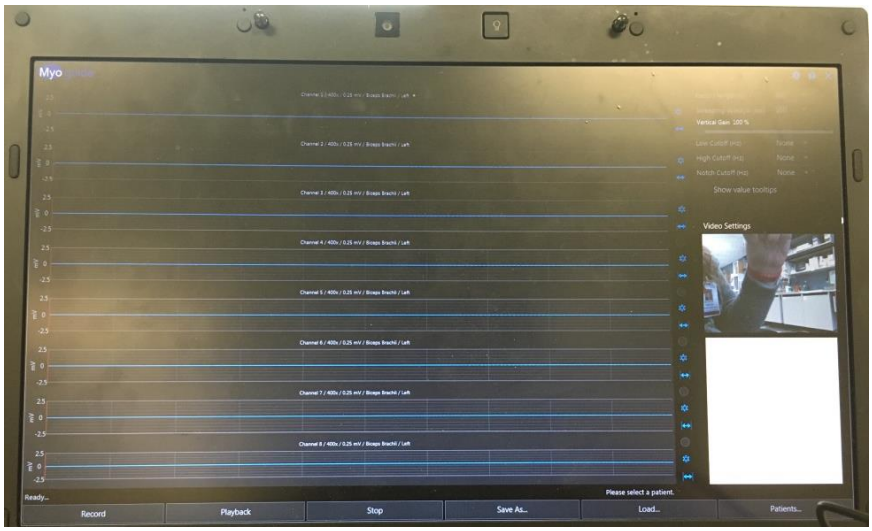


Figure 3.3. Myoguide system Intronix model 8008

5. Standard Web Camera *(Logitech®)*: The camera was used to records videos of the patient motions in widescreen Full HD 1080p at 30 frames per second. This was needed in order to have visual input to see the motions performed and how they were performed (see Figure 3.4).

Figure 3.4. Logitech camera used in the study

6. Load Cell *(American Archery Products® M110 Digital Bow Hang Scale 110lbs)*: A digital scale that measures both peak weight and holding weight, while providing superior accuracy to 0.05 lbs. was needed for measuring the maximum force produced during the flexion MVC and extension MVC (see Figure 3.5).

Figure 3.5. Digital scale used to measure force of subjects

7. Inertial Measurement Unit (*STEVAL-MKI108V2, STMicroelectronics*®): A 9-axis inertial measurement units (IMU) was used for measuring the angle of the elbow during flexion and extension (see Figure 3.6).

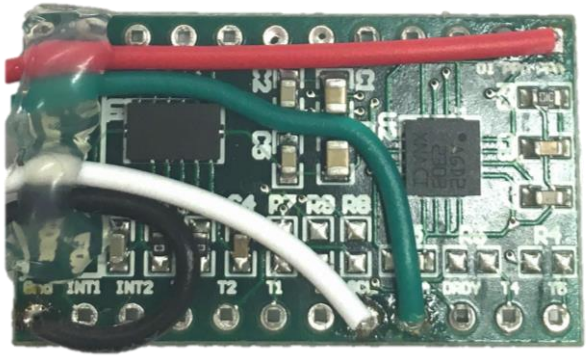


Figure 3.6. IMU

8. Bipolar Electrodes *(Ambu® Blue Sensor NF)*: Sets of single use bipolar single patient use floating electrodes were used to detect potential differences within the muscles (see Figure 3.7). Details of the electrodes and how they were placed are described in the next section.

Figure 3.7. Ambu bipolar electrodes

3.1.1 Electrode Placement

The electrodes used are “floating electrodes,” which are ideal for dynamic movements as they are housed in gel or electrode paste creating a bridge between the electrode and the skin. This potentiates the EMG signal from the surface of the skin to the electrode while providing a cushioning mechanism that absorbs the movement of the electrode thus reducing motion artifact.

The electrodes were placed in correspondence with the SENIAM project (Surface EMG for Non-invasive Assessment of Muscles) [55]. This project illustrates recommendations for sensor placement used by various researchers around the world. The distance between the electrodes was kept at approximately 2 centimeters for all muscle groups as suggested by SENIAM. Some of the muscles that were not included in SENIAM were placed in accordance with literature guidelines. The placement of electrodes is shown in Figures 3.8 and 3.9.

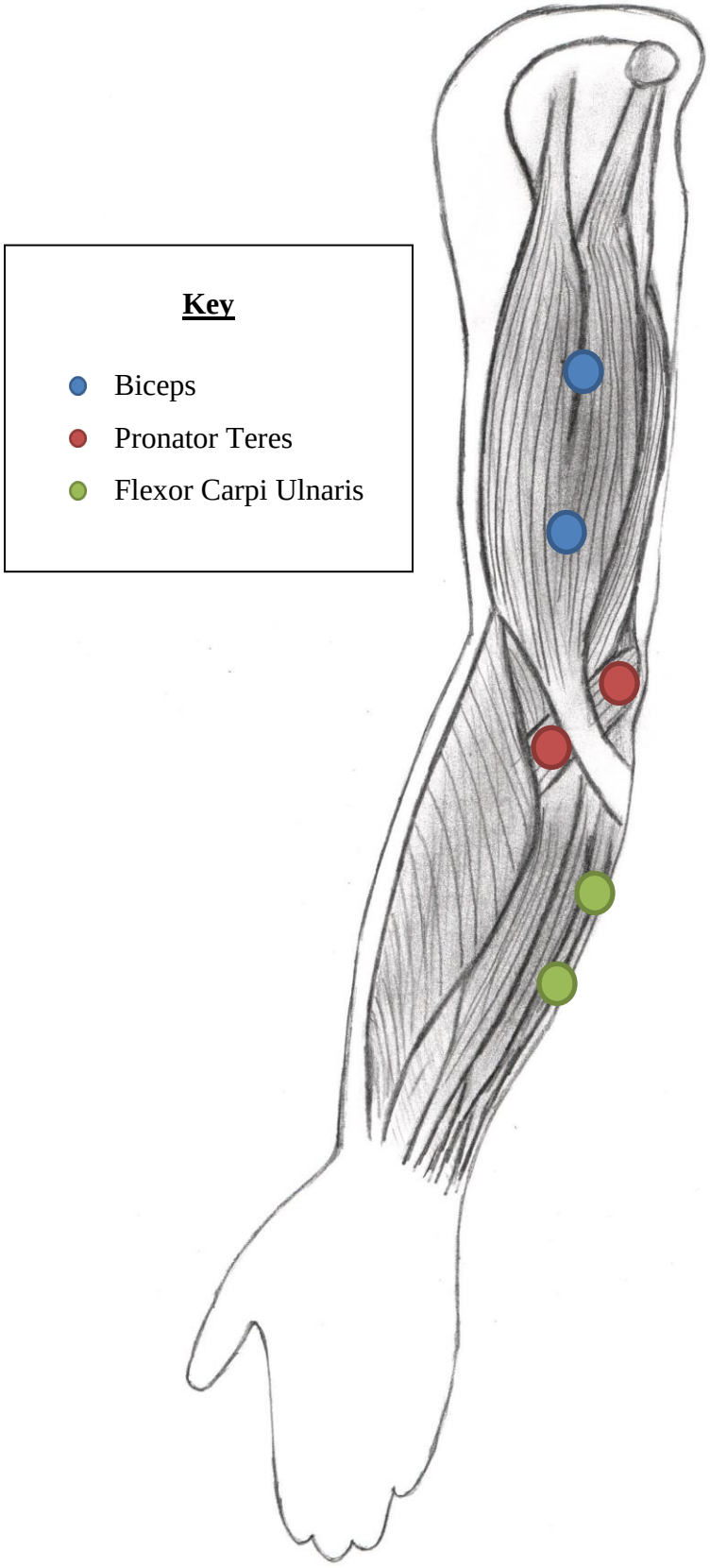


Figure 3.8. Anterior Arm Electrode Placement

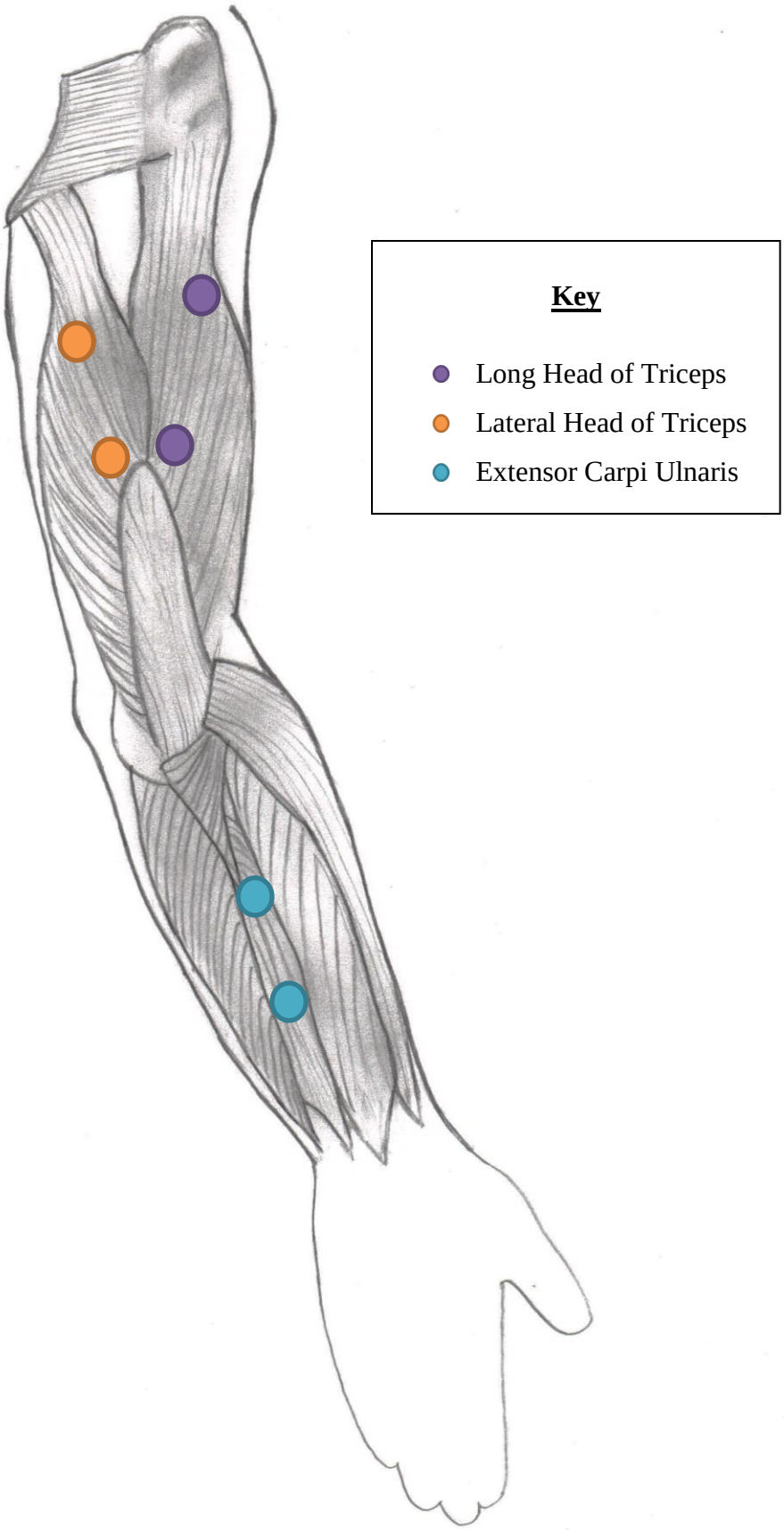


Figure 3.9. Posterior Arm Electrode Placement

3.2 Skin Preparation

Proper electrode-skin contact is crucial for good quality EMG signals to reduce noise and artefacts [55]. In order for the electrodes to have optimum skin contact, proper skin preparation is required. The SENIAM project recommends cleaning the skin with alcohol to remove any surface dirt from the skin in order for the electrodes to stick properly. This was executed for this work.

3.3 Experimental Protocol

3.3.1 Pilot Studies

Two separate pilot studies were conducted to collect data from healthy individuals and patients. Approval from the Human Research Ethics Board at Western University was obtained prior to the start of the trials. The instruments used, EMG placement techniques, and skin preparation were kept constant throughout the two studies. Sagittal movements were executed in a supine position. The upper arm was aligned with the trunk. The shoulder was not fixed to increase comfort; however, the subjects were instructed to stay as still as possible. The details of the two studies are presented below.

3.3.1.1 Healthy Individuals Pilot Study

The first study involved only healthy individuals performing the elbow flexion–extension motion only. They executed the motions while carrying a 5 pound-weight while wearing a mechanical brace that limited their angles of flexion and extension to a particular range. Since motions performed at different arm positions are proven to affect the activation patterns of the arm muscles, all the motions were carried out with the wrist in neutral position [56].

The data collection protocol consisted of the following steps:

1. The patient was seated on a comfortable chair.
2. The patient was asked to report their weight and height.
3. The length of their arm and hand was measured.
4. The circumference of their arm and hand was measured.
5. The areas of interest were wiped with alcohol pads.
6. The electrodes were attached about 2 cm apart in the direction of the muscle fibres.

7. The ground electrode was placed on the olecranon.
8. The mechanical brace was placed on the arm and secured with padded straps. This brace limits the arm motion to one of the natural directions of motion (flexion–extension).
9. The system is initiated while the subject is at rest and the channels are examined to make sure a baseline signal is being collected.
10. Following the baseline check, the subject is asked to contract some muscles to make sure the software shows EMG bursts in order to be certain all the electrodes are in the correct place.
11. The subject was given a 5-pound weight to be carried on their hand.
12. The subject was instructed to perform elbow flexion–extension tasks (biceps-curls) requiring them to move their lower arm through a specified range at a low speed.
13. The subject was instructed to perform 3 sets of 3 repetitions at 6 different ranges of motion (for a total of 54 repetitions). The ranges were as follows: 0–45 degrees, 0–60 degrees, 0–90 degrees, 0–120 degrees, 45–105 degrees, and 90–120 degrees.
14. Subjects performed an un-resisted maximum voluntary contraction (MVC) where they tensed up their arm as hard as they can to activate all the muscles at once.

3.3.1.2 Patient Pilot Study

The second study involved patients performing numerous motions including elbow flexion–extension, pronation–supination, and wrist flexion–extension. The motions were carried out with the wrist in neutral position. Unlike the healthy pilot study, patients were not carrying any weights and were not placed in the mechanical brace.

3.3.1.2.1 Pilot Data Collection Protocol for Patients

1. The patient was seated on a comfortable chair.
2. The patient was asked to report their weight and height.
3. The length of their arm and hand was measured.
4. The circumference of their arm and hand was measured,
5. The areas of interest were wiped with alcohol pads.
6. The electrodes were attached about 2 cm apart in the direction of the muscle fibres.

7. The ground electrode was placed on the olecranon.
8. The system is initiated while the subject is at rest and the channels are examined to make sure a baseline signal is being collected.
9. Following the baseline check, the subject is asked to contract some muscles to make sure the software shows EMG bursts in order to be certain all the electrodes are in the correct place. Patients performed 3 repetitions of the following motions:
    - Unresisted MVC
    - Elbow Flexion–Extension
    - Pronation–Supination
    - Wrist Flexion–Extension
    - Ulnar–Radial Deviation
    - Hand Open–Close

3.3.2 Iterations

Following the first pilot study trials, the protocol was modified in order to accommodate patients' capabilities. Since not all patients had full range of motion, it was unsafe to place their arms in the OSSUR brace and ask them to reach specific angles set by the brace. Therefore, the OSSUR brace was removed from the protocol. After the removal of the brace, the range of motion of the subjects became unknown. An IMU was placed on the wrist of each subject to calculate the elbow position and determine the elbow angle. Moreover, a resisted MVC was implemented to provide a more realistic measure of the maximum contraction. The motion was incorporated in both the flexion and extension directions in order to obtain the MVC of both the biceps and triceps. While doing so, the force produced through these motions was also measured using a force sensor. This was done through the placement of the wrist of the subjects in a cuff connected to a scale. They were then asked to move in both the flexion and extension motions as hard as they could and they were asked to hold the contraction for about 5 seconds. In addition to the motions of the elbow and wrist presented in the second pilot study of patients, another motion was prescribed where the subject was asked to press their hand down as hard as they could on a ball, and to hold the contraction for about 5 seconds. This motion provides an unstable surface for the joint so that the muscles work together to try and stabilize the arm in place. This assesses the neuromuscular control of the arm and allows for the evaluation of firing patterns. Furthermore, in addition to the

general biometric data collected, information about the injury was obtained, in order to assess if different injuries cause different trends of activation. Finally, to check that the electrodes were placed on the correct areas of the muscles, a baseline check was incorporated into the protocol. This involved recording the EMG while the individual was at rest. If there were irregularities in the signal of a specific channel, the ground electrode was checked along with the electrodes of the channel to assure that it was attached properly to the individual. Additionally, EMG burst checks were done by asking the individual to contract all arm muscles and relax them multiple times to ensure that the bursts were showing on the screen, thus confirming that the electrodes were in the proper areas of the muscles.

3.3.3 Final Experimental Protocol

As mentioned in the iterations section previously, some modifications were made to the pilot trials in order to encompass motions that a variety of individuals can perform within their own limits or restrictions set by their therapists. The following protocol was the final protocol used to carry out the trials, with removal of specific motions if considered unsafe by the patient's therapist:

1. The subject was seated on a comfortable chair
2. If the subject was a patient, he or she was asked to provide biometric data such as age, height, source of trauma, and what type of injury they sustained. If not, age and height was collected from healthy individuals.
3. The length of their arm and hand was measured.
4. The circumference of their arm and hand was measured.
5. The areas of interest were wiped down with alcohol pads.
6. The electrodes were attached about 2 cm apart in direction of the muscle fibres.
7. The dominant belly portion was used for best selectivity.
8. The ground electrode was placed on the olecranon.
9. A baseline check was conducted.
10. An EMG bursts check was also performed.

The subjects completed 3 repetitions of the following motions except for the MVCs:

Maximum Voluntary Contraction of Biceps

Biceps MVC was performed by placing the wrist in a cuff connected to a load cell with the elbow at 90 degrees and the wrist is in neutral position. The subject was then asked to pull upwards in the direction of flexion as hard as they can; however, the cuff does not allow them to achieve full flexion as depicted in Figure 3.10 below. Subjects were asked to hold this contraction for 5 seconds.

Figure 3.10. Subject performing Biceps MVC

Maximum Voluntary Contraction of Triceps

Triceps MVC was performed by placing the wrist in a cuff connected to a load cell with the elbow at 90 degrees and the wrist is in neutral position. The subject was then asked to pull downwards in the direction of extension as hard as they can; nevertheless, the cuff does not allow them to achieve full extension as depicted in Figure 3.11 below. Subjects were asked to hold this contraction for 5 seconds.

Figure 3.11. Subject performing Triceps MVC

Elbow Flexion–Extension

The flexion–extension motion of the elbow is simply achieved by keeping the shoulder aligned with the torso and solely moving the lower arm (see Figure 3.12 below). Subjects were asked to do this motion within their maximum capable range with their wrist in neutral position. For healthy individuals this is from 0°–120° with a functional range of 75°–120° [57]. A functional range is the minimum required range to perform activities of daily living.

Figure 3.12. Person with right elbow extended (left), flexed at 90 degrees (middle), and fully flexed (right)

Wrist Flexion–Extension

In addition to elbow flexion–extension, wrist motions were also explored. Subjects performed flexion and extension of the wrist within their capable range with their wrist in neutral position (see Figure 3.13).

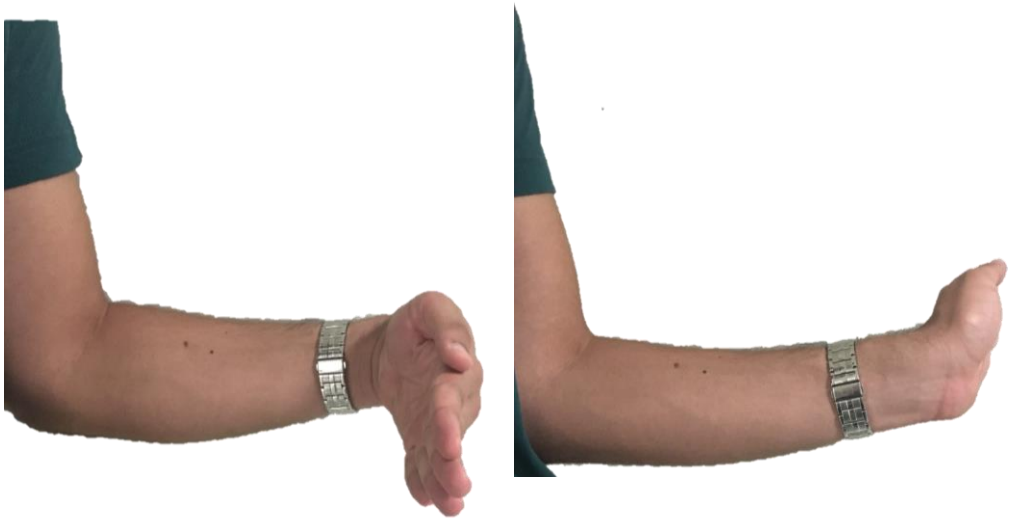


Figure 3.13. Left wrist flexed (left) and extended (right)

Hand Open–Close

The simple closing and opening of the hand of interest was also executed. This entails having the fingers spread out and opened followed by the closing of the fingers through making a fist with their wrist in neutral position as portrayed in Figure 3.14 on the next page.

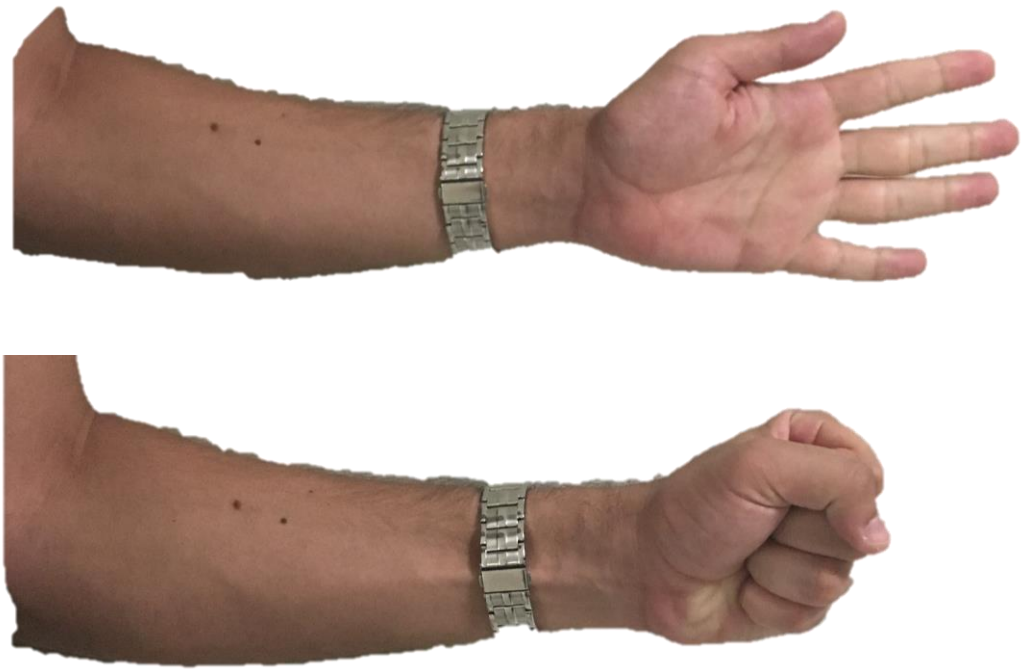


Figure 3.14. Left hand open (top) and closed in a fist (bottom)

Ulnar–Radial Deviation

The next motion performed was ulnar–radial deviation. This is where the hand deviates towards the ulna in a downward motion for the ulnar deviation then moves upwards towards the radius to achieve radial deviation (Figure 3.15). This motion was executed with the wrist in neutral position.

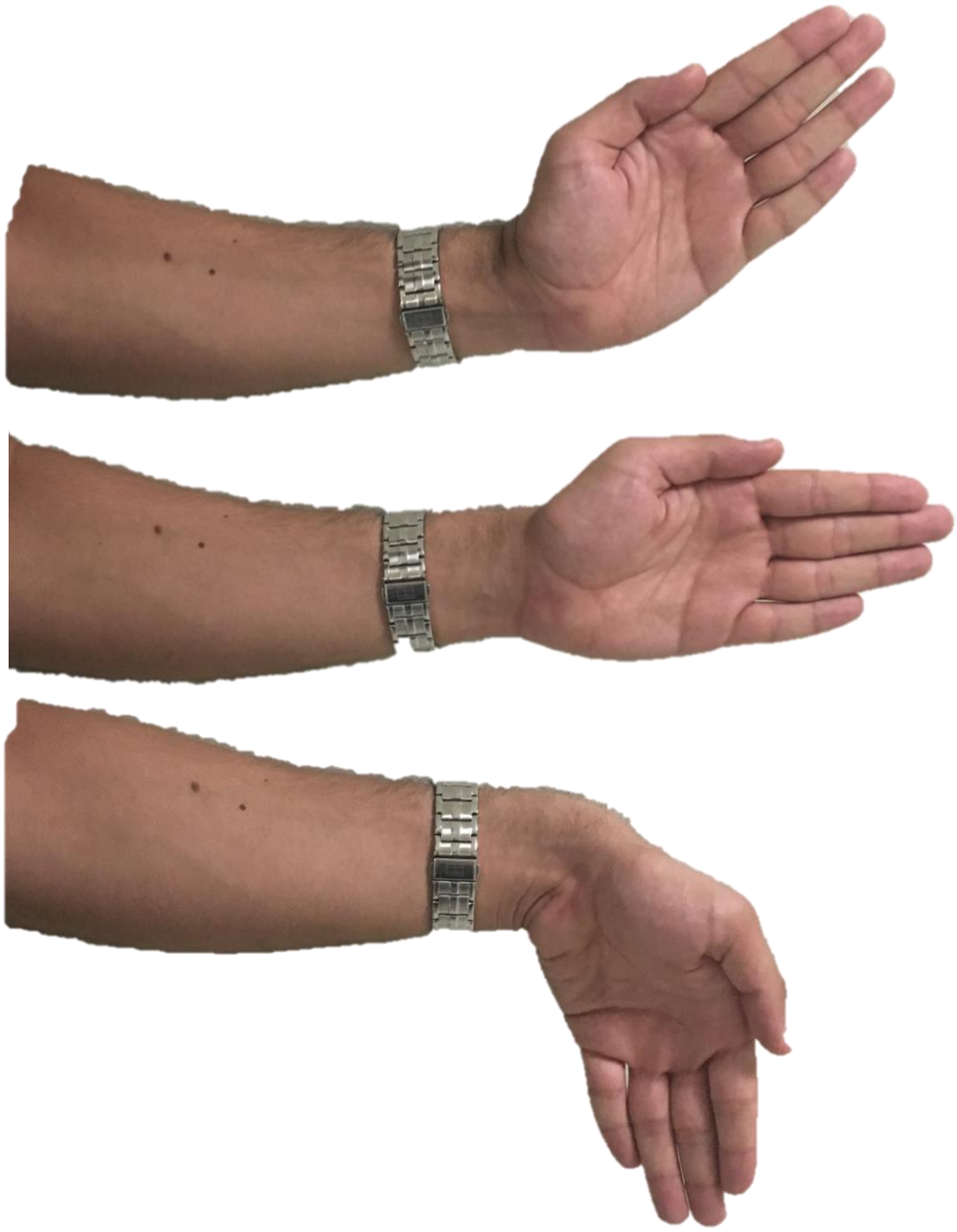


Figure 3.15. Left wrist in radial deviation (top), neutral (middle), and in ulnar deviation (bottom)

Pronation–Supination

Pronation is achieved when the lower arm is turned to make the palm face downwards. In contrast, supination occurs when the lower arm is turned to make the palm face upwards. These motions are represented below in Figure 3.16.

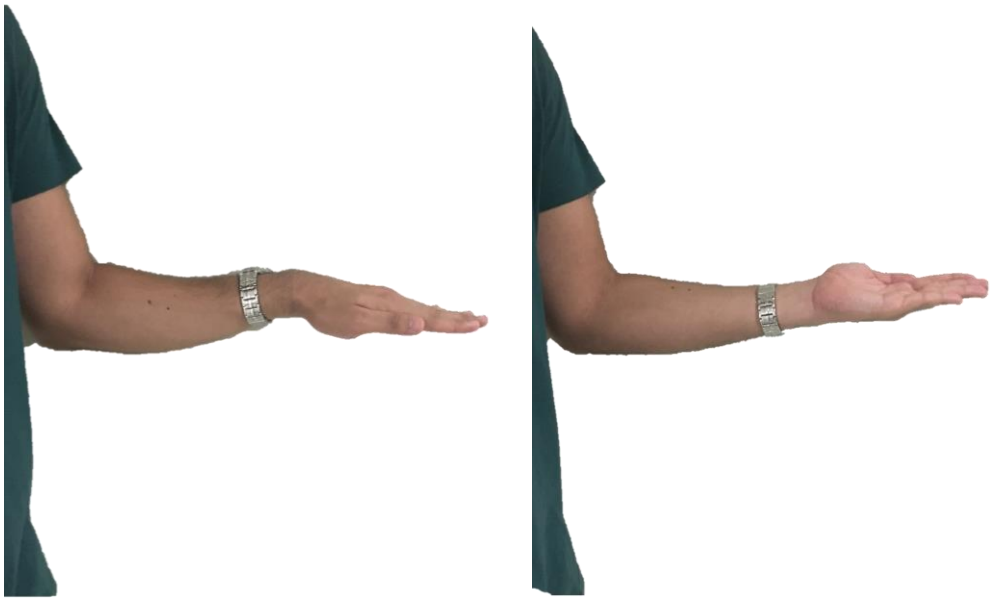


Figure 3.16. Left arm pronated (left) and supinated (right)

Pressing on a Ball

Lastly, pressing down on a ball is the last motion the subjects were asked to do. The subject was asked to place their palm around a ball with the elbow at a 90-degree angle. The subject then pressed down as hard as they can while stabilizing the ball in place without having it roll to either side (see Figure 3.17).

Figure 3.17. Right hand pressing down on a ball

This concludes the motions performed by the subjects. The signals obtained from these motions will be discussed next. Pure biological signals are almost impossible to obtain, if not impossible [58]. Consequently, it is essential for the signals to go through a series of processing phases in order to remove the maximum amount of noise leaving only the biological signal. This allows the signal to be quantified through various means discussed in detail in this thesis. Data analysis was performed off-line using MATLAB (MathWorks, Version R2014b).

3.3.4 Differential Amplification

Following action potential propagation recorded by the electrodes, the first step is for the signal to be amplified or made larger. The amplification factor is called gain. The signal size is dependent on how big the gain is set to. The gain was adjusted to achieve the best possible signal resolution within the limited time of the subject.

3.3.5 Filtering

After signal amplification, the signal goes through multiple levels of processing. The first level of processing is noise removal. This is a series of steps aimed at decreasing noise as much as possible. A band pass filter is a filter that only allows a specific range of frequencies to pass through. According to the literature, a band-pass filter of 20 to 500 Hz was most commonly used [8][29][59]. In accordance with the literature

recommendations, an analog band-pass filter of 20 to 500 Hz was used where the raw signal is filtered prior to being digitized. The lower cutoff mainly removes electrical noise as well as biological and movement artifacts while the upper cutoff excludes noise at the site of the electrode. The other dominant source of the electrical noise available within the signal is at 60 Hz because of the power line radiation [60]. Although a notch filter can be applied and theoretically only remove the power line frequency, in practical implementations, a notch filter also removes portions of adjacent frequency components. Since the dominant energy of the signal is within the 50–100 Hz range, using a notch filter will remove important information within the important information range and therefore is not advisable.

3.3.6 Full Wave Signal Rectification

Regardless of what processing the signal must undergo, all processing begins with a common step: signal rectification. This is where the absolute value of the signal is taken and all the negative values become positive causing the signal to exclusively reside above the zero point [26][61] (see Figure 3.18). This technique maintains the energy level of the signal [58]. Since the signal oscillates about zero, the mean will be near zero if an average is taken of a raw signal without rectification. Therefore it is a crucial initial step to rectify the signal before any calculation can be made.

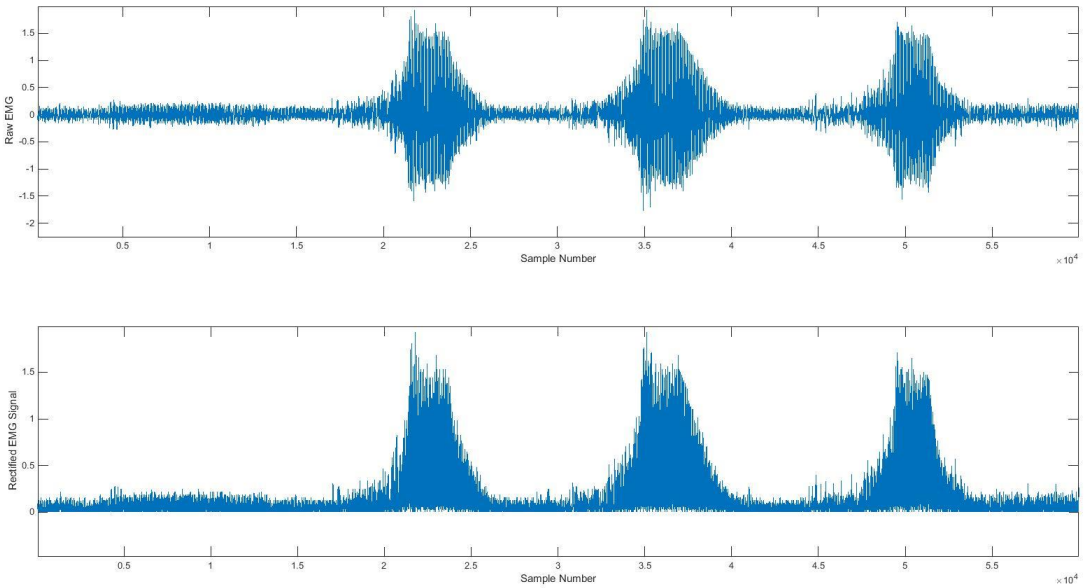


Figure 3.18. Raw Biceps contraction in elbow flexion and extension signal (top) and rectified (bottom)

3.3.7 Linear Envelope

The next step is creating a linear envelope (see Figure 3.19). The linear envelope is the most common demodulation technique used to extract information from EMG [37] . A discrete version of a traditional low pass filter, called the Butterworth filter, was used in this thesis [61] [62]. This is an infinite impulse response filter that was applied in both forward and backward directions resulting in a zero phase shift. The literature recommends between 5 and 100 Hz as the cutoff frequency. The lower limit of this range, 5, was used in this thesis.

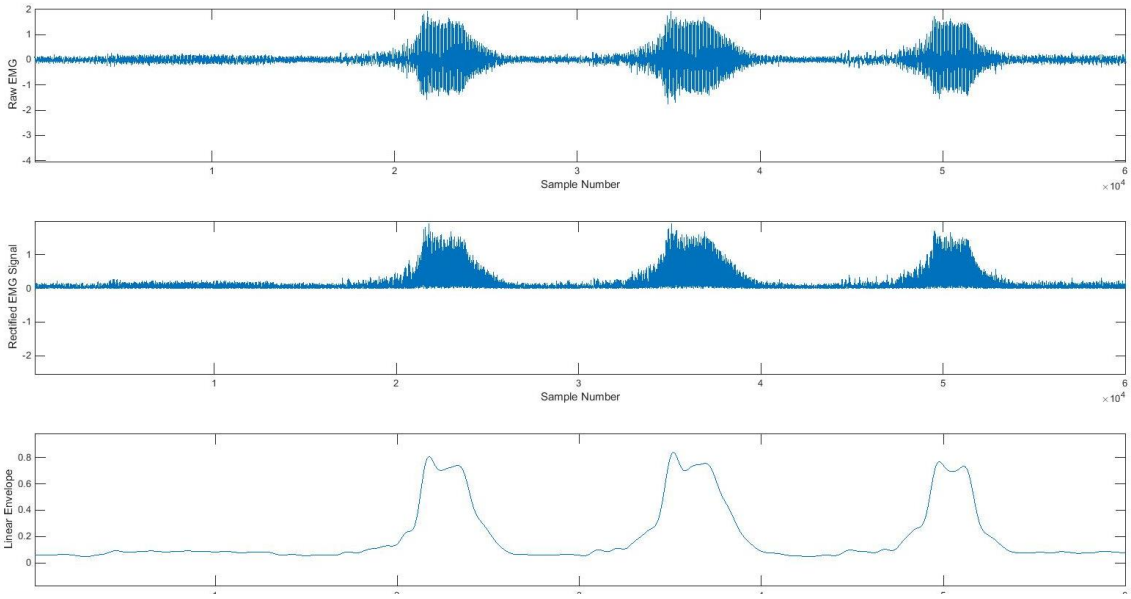


Figure 3.19. Raw biceps contraction in elbow flexion and extension signal (top), rectified (middle), and linear envelope of signal (bottom)

3.3.8 Normalization

After the signals are collected, they must be in a state to be compared to other signals for analysis. To do so, a process called normalization must be conducted. Normalization is a method of relative measure of individual muscles' activity in comparison with the maximum muscle activity obtained at a similar angle [41] [29] [8] [30] [63]. This is necessary when a comparison is to be made on the same muscle on different days, between different individuals, or between different muscles. This is usually done by

dividing the EMG signals of the task by a reference EMG value obtained from that same muscle. This reference value can be obtained through several ways, as follows:

1. Maximum Voluntary Contraction (MVC): The most common method involves having a person perform an isometric contraction where the maximum effort is exerted and recorded. All muscle functions are then reduced to this common value as a percentage from 0% to 100%

2. Submaximal Contraction: The second most common method involves the subject performing a dynamic motion while peak values are obtained from it. The average of the peaks is then used as the reference for all muscle functions.

Normalization using MVC is considered to be more sensitive in contractions that require more effort, while submaximal contractions are more sensitive with lower levels of activation [29]. The MVC method was used for all subjects except for patients who were not allowed to perform resisted motions at the time of the data collection. Instead, submaximal contraction normalization was executed for those subjects.

Following the normalization of the signals obtained from the various motions, different metrics, as explained in the next section, were extracted from the signals and compared within each muscle group between healthy individuals and patients.

3.3.9 EMG Based Metrics

The previous sections described the signal processing techniques in order to prime the signal for information to be extracted. Accordingly, the following sections present the metrics examined and used to extract information from the processed signals, in both the time and frequency domain. Feature extraction is a method to extract the valuable information within a surface EMG signal and remove the undesirable EMG data[64]. EMG based metrics can be divided into three main groups: time domain, frequency domain, and time-frequency or time-scale representation [65][66]. In this thesis, the first two groups have been examined as features in the last group, time-frequency/time-scale features, cannot be reported on their own as they require reduction of high dimensions before being classified [67]. Whereas the first two groups have been used as dimensionality reduction methods [64]. Data analysis was performed off-line using MATLAB (The MathWorks Inc., Natick, MA, USA, Version R2014b).

3.3.9.1 Time Domain

Metrics in the time domain are fast and easily implemented. This is because they are calculated based on raw EMG time series [65] [68] [69]. Features in this domain have been used widely in both the medical and engineering fields of researches and practices. Although the EMG signal is non-stationary, meaning it changes in statistical properties over time, it is assumed to be stationary in this domain [70]. This is a disadvantage as it can cause variations when dynamic motions are recorded. Additionally, as a lot of the metrics in this domain heavily depend on amplitude values, any interference in the collection process can negatively affect the signal and thus filtering is important. This section outlines the features extracted in the time domain. Formulae for each metric are presented; all of these calculations were done using MATLAB functions.

3.3.9.1.1 Average Rectified Value (ARV) [37] [66] [68] [69]

The first metric examined is ARV. ARV is used to quantify magnitude of muscle activity by detecting changes due to MU recruitment, firing rate, or muscle fibre conduction velocity. This method is fits well for low contractions and fatigues muscles [71]. The equation of ARV is as follows:

$$ARV = \frac{1}{T}\sum_{t=1}^{T} |EMG\ (t_i)|$$

where $EMG(t_i)$ is the absolute value of a datum of EMG in a data window and T is the interval. This calculation is done using the absolute value of the data window and is similar to integration.

3.3.9.1.2 Root Mean Square (RMS) [37] [66] [71]

Next, RMS was examined. This method is dependent on amplitude and has been shown to fit better at high levels of contraction. During each repetition of motion, the RMS amplitude was calculated and averaged throughout. RMS is calculated using the succeeding function:

$$RMS = \sqrt{\frac{1}{T}\sum_{t=1}^{T} EMG^2(t_i)}$$

where $EMG(t_i)$ is the absolute value of a datum of EMG in a data window and *T* is the interval. This calculation is done on the raw data for a data window and is used quantify magnitude of muscle activity through squaring the data, summing the squares dividing the sum by the number of observations, and then taking the square root.

3.3.9.1.3 Mean Spike Amplitude (MSA) [37]

Another metric examined in the time domain is MSA. To obtain the mean value, single spike amplitude must be first defined and determined. An EMG spike is a pair of upward and downward deflections that cross the isoelectric line and are greater than 95% confidence interval. A peak on the other hand, is a pair of upward and downward deflections that occur within a spike. These are ignored in MSA calculations denoted with an "X" in Figure 3.20.

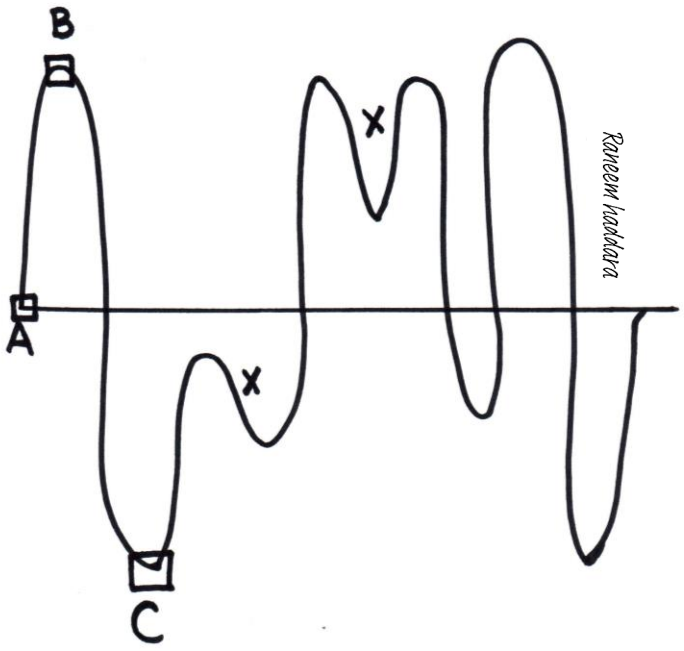


Figure 3.20. Single Spike Amplitude Example

Single Spike Amplitude (SA) is calculated using the following equation:

$$SA_i = \frac{(B_y - A_y) + (B_y - C_y)}{2}$$

where *Y* is the amplitude value at time *(t).* The mean of the SA across the signal is then calculated using the equation below.

On the other hand, MSA is simply obtaining the mean of the SA as shown in the following equation:

$$MSA = \frac{1}{NS}\sum_{i=1}^{NS} SA_i$$

where *NS* is total number of spikes within a data window. This method of analysis also is used to quantify the magnitude of the muscle activity and is highly correlated with RMS amplitude. Additionally, it is a highly stable method of calculation during dynamic contractions.

3.3.9.1.4 Zero Crossings (ZC) [64] [68] [69]

Finally, ZC is the last metric to be discussed in the time domain. Zero crossings are simply the number of times the signal crosses the baseline x-axis i.e. reaches 0 millivolts. The thicker the tracing of the raw EMG signal, the stronger the contraction.

3.3.9.2 Frequency Domain

The following section will outline the features extracted in the frequency domain. Formulae shown here are just for understanding purposes. Data analysis was performed off-line using MATLAB (The MathWorks Inc., Natick, MA, USA, Version R2014b).

3.3.9.2.1 Power Spectral Density (PSD) Analysis [37] [66]

The other metric examined is PSD. The following is the formula describing is:

$$PSD = \phi(\omega) = X(\omega)X^*(\omega) = |X(\omega)|^2$$

where $X(\omega)$ is the Fourier transform of $x(t)$ and $X^*(\omega)$ is the complex conjugate of $X(\omega)$, the two are multiplied giving the squared magnitude of the Fourier transform.

The frequency spectrum is not used in the literature due to its stochastic properties; the spectral mean value is zero [37]. The solution to this problem is similar to that of the summing of deviation scores by squaring the values. Obtaining the power spectral density function of the signal through squaring the magnitude of each frequency component of the Fourier series demonstrates the power spectrum. Frequency shifts in the power spectrum can distinguish between normal muscle function and impaired muscle function [50].

It has been shown in literature that the PSD function can be characterized by two parameters: mean power frequency (MNF) and median power frequency (MDF). These parameters are thought to be sensitive to conduction velocity-motor unit recruitment and rate coding [37]. MNF and MDF were extracted from the signals.

The method of data collection and analysis was explained in this chapter. The pilot study was explained in detail as well as the iterations that followed based on the trial run. Moreover, all the instrumentation used was portrayed. Following the data collection protocol, the data analysis protocol was discussed. The formulae and methods used in pre-processing and processing of the signals were described. There were five metrics applied in this thesis; the time domain metrics were RMS, ARV, MSA, and ZC while the frequency domain metric was PSD, which included MNF and MDF. The next section will report the results of these metrics explored.

4 Results and Discussion

According to the analysis of the time domain and frequency domain metrics presented in the previous chapter, two analyses were executed. Firstly, a general comparison between the healthy population and the patient population was done with all of the metrics mentioned. Secondly, a comparison within the patient population between subjects in the early rehabilitation group (0–1 month) and a late stage (4+ months) rehabilitation group.

The statistical analysis performed was a general linear model repeated measures study. Each repetition within each motion was considered the repeated measure for a total of 3 repetitions. The analysis was done within subjects using the values of the metrics in repetitions and between subjects using health. A Post Hoc Tukey test was applied

during the second type of analysis within the patient population. The Statistical Package for Social Sciences (SPSS) was used to run all of these analyses. Statistical significance of the 0.05 level was considered.

In the first analysis, 16 healthy individuals and 17 patients were analyzed. However, due to some trial errors, some subjects were removed from the individual analyses when the raw data was deemed compromised. A maximum of 4 subjects were removed. In most metrics, an average of 2 subjects were removed. Likewise, in the second analysis within patients, there were about 5 patients in each group. The least amount in a group was 2 subjects. In the tables of results, the letter “N” shows the number of subjects analyzed during each motion.

The following chapter will focus on the analysis of the metrics that showed multiple cases of significance. For further information on the non-significant metrics, see Appendix C. The frequency domain metrics seldom showed statistical significance and thus have been excluded from the following discussion. The metrics that proved to discriminate between the healthy and the patient population were used in the second analysis to assess whether they were able to distinguish between patients at the start of their therapy within a month after injury or surgery and those at four or more months post injury or surgery.

4.1 Root Mean Square

RMS is a very widespread metric of analyzing EMG. It was initially used to distinguish between healthy individuals and patients. Statistically significant information is shown in Table 5 below. A further analysis to distinguish between patients in the first month of their versus those towards the end of the therapy at 4+ months was conducted. Likewise the statistically significant cases are summarized and presented in Table 4.1 and shown in details in Table 4.2, 4.3, 4.4, 4.5, 4.5, 4.7, and 4.7. These detailed tables depict information about each repetition individually. The number of subjects the data was drawn from is shown as (N). The statistically significant values are reported and discussed in this section.

Table 4.1. Statistical analysis comparing healthy individuals to patients using RMS

Motion	Muscle	Mean Healthy/ mV	Mean Patients/ mV	SE Healthy	SE Patients	p Value	*F* statistic
EFE	ECU	0.021	0.104	0.028	0.025	0.037	4.836
PS	ECU	0.015	0.095	0.019	0.018	0.005	9.281
PS	PT	0.028	0.103	0.023	0.023	0.028	5.348
HOC	PT	0.025	0.083	0.02	0.019	0.045	4.497
HOC	FCU	0.031	0.215	0.056	0.054	0.026	5.635
HOC	ECU	0.019	0.15	0.035	0.033	0.012	7.395
Ball	FCU	0.051	0.135	0.026	0.025	0.03	5.281

Table 4.2. Statistical analysis of FCU in EFE motion within each repetition comparing healthy individuals to patients using RMS

	Health	Mean	Std. Deviation	N
Flexor Carpi Ulnaris in Rep 1 Elbow Flexion	Healthy	.104	.153	13
	Patient	.126	.119	16
	Total	.116	.133	29
Flexor Carpi Ulnaris in Rep 1 Elbow Extension	Healthy	.0721	.108	13
	Patient	.126	.154	16
	Total	.102	.136	29
Flexor Carpi Ulnaris in Rep 2 Elbow Flexion	Healthy	.0684	.100	13
	Patient	.158	.176	16
	Total	.118	.151	29
Flexor Carpi Ulnaris in Rep 2 Elbow Extension	Healthy	.092	.131	13
	Patient	.113	.139	16
	Total	.104	.134	29
Flexor Carpi Ulnaris in Rep 3 Elbow Flexion	Healthy	.111	.162	13
	Patient	.134	.137	16
	Total	.124	.147	29
Flexor Carpi Ulnaris in Rep 3 Elbow Extension	Healthy	.0619	.0953	13
	Patient	.182	.220	16
	Total	.128	.183	29

Table 4.3. Statistical analysis of ECU in PS motion within each repetition comparing healthy individuals to patients using RMS

	Health	Mean	Std. Deviation	N
Extensor Carpi Ulnaris in Rep 1 in Pronation	Healthy	.014	.011	16
	Patient	.098	.116	17
	Total	.057	.093	33
Extensor Carpi Ulnaris in Rep 1 in Supination	Healthy	.017	.015	16
	Patient	.094	.102	17
	Total	.057	.083	33
Extensor Carpi Ulnaris in Rep 2 in Pronation	Healthy	.016	.014	16
	Patient	.098	.112	17
	Total	.058	.090	33
Extensor Carpi Ulnaris in Rep 2 in Supination	Healthy	.015	.014	16
	Patient	.092	.096	17
	Total	.055	.079	33
Extensor Carpi Ulnaris in Rep 3 in Pronation	Healthy	.014	.012	16
	Patient	.094	.108	17
	Total	.055	.087	33
Extensor Carpi Ulnaris in Rep 3 in Supination	Healthy	.015	.015	16
	Patient	.093	.097	17
	Total	.055	.080	33

Table 4.4. Statistical analysis of PT in PS motion within each repetition comparing healthy individuals to patients using RMS

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 Pronation	Healthy	.046	.046	16
	Patient	.118	.143	17
	Total	.083	.112	33
Pronator Teres in Rep 1 Supination	Healthy	.021	.019	16
	Patient	.078	.119	17
	Total	.050	.090	33
Pronator Teres in Rep 2 Pronation	Healthy	.029	.024	16
	Patient	.129	.151	17
	Total	.081	.119	33

Pronator Teres in Rep 2 Supination	Healthy	.019	.019	16
	Patient	.078	.122	17
	Total	.049	.092	33
Pronator Teres in Rep 3 Pronation	Healthy	.033	.030	16
	Patient	.129	.149	17
	Total	.082	.118	33
Pronator Teres in Rep 3 Supination	Healthy	.018	.014	16
	Patient	.085	.133	17
	Total	.052	.100	33

Table 4.5. Statistical analysis of PT in HOC motion within each repetition comparing healthy individuals to patients using RMS

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep1 in Hand Open	Healthy	.026	.032	12
	Patient	.084	.089	13
	Total	.056	.073	25
Pronator Teres in Rep 1 in Hand Close	Healthy	.021	.029	12
	Patient	.084	.096	13
	Total	.054	.077	25
Pronator Teres in Rep 2 in Hand Open	Healthy	.029	.034	12
	Patient	.085	.090	13
	Total	.058	.074	25
Pronator Teres in Rep 2 in Hand Close	Healthy	.021	.032	12
	Patient	.085	.094	13
	Total	.054	.077	25
Pronator Teres in Rep 3 in Hand Open	Healthy	.033	.036	12
	Patient	.082	.089	13
	Total	.058	.072	25
Pronator Teres in Rep 3 in Hand Close	Healthy	.018	.026	12
	Patient	.082	.092	13
	Total	.051	.075	25

Table 4.6. Statistical analysis of FCU in HOC motion within each repetition comparing healthy individuals to patients using RMS

	Health	Mean	Std. Deviation	N
Flexor Carpi Ulnaris in Rep 1 in Hand Open	Healthy	.036	.035	12
	Patient	.248	.400	13
	Total	.146	.304	25
Flexor Carpi Ulnaris in Rep 1 in Hand Close	Healthy	.023	.018	12
	Patient	.197	.287	13
	Total	.113	.222	25
Flexor Carpi Ulnaris in Rep 1 in Hand Open	Healthy	.038	.038	12
	Patient	.224	.319	13
	Total	.134	.246	25
Flexor Carpi Ulnaris in Rep 1 in Hand Close	Healthy	.025	.027	12
	Patient	.220	.351	13
	Total	.126	.268	25
Flexor Carpi Ulnaris in Rep 1 in Hand Open	Healthy	.043	.048	12
	Patient	.218	.288	13
	Total	.134	.225	25
Flexor Carpi Ulnaris in Rep 1 in Hand Close	Healthy	.023	.022	12
	Patient	.184	.253	13
	Total	.107	.197	25

Table 4.7. Statistical analysis of ECU in HOC motion within each repetition comparing healthy individuals to patients using RMS

	Health	Mean	Std. Deviation	N
Extensor Carpi Ulnaris in Rep 1 in Hand Open	Healthy	.020	.021	12
	Patient	.148	.161	13
	Total	.087	.132	25
Extensor Carpi Ulnaris in Rep 1 in Hand Close	Healthy	.016	.016	12
	Patient	.118	.143	13
	Total	.069	.114	25
Extensor Carpi Ulnaris in Rep 2 in Hand Open	Healthy	.024	.022	12
	Patient	.187	.242	13
	Total	.109	.191	25
Extensor Carpi Ulnaris in Rep 2 in Hand	Healthy	.018	.012	12

Close	Patient	.144	.163	13
	Total	.083	.132	25
Extensor Carpi Ulnaris in Rep 3 in Hand Open	Healthy	.022	.018	12
	Patient	.161	.176	13
	Total	.094	.144	25
Extensor Carpi Ulnaris in Rep 3 in Hand Close	Healthy	.017	.012	12
	Patient	.141	.160	13
	Total	.081	.130	25

Table 4.8. Statistical analysis of FCU in Ball Press motion within each repetition comparing healthy individuals to patients using RMS

	Health	**Mean**	**Std. Deviation**	**N**
Flexor Carpi Ulnaris in Rep 1 Ball Press	Healthy	.084	.094	14
	Patient	.187	.158	15
	Total	.137	.139	29
Flexor Carpi Ulnaris in Rep 1 Ball Relax	Healthy	.028	.041	14
	Patient	.087	.108	15
	Total	.058	.086	29
Flexor Carpi Ulnaris in Rep 2 Ball Press	Healthy	.080	.093	14
	Patient	.185	.158	15
	Total	.134	.139	29
Flexor Carpi Ulnaris in Rep 2 Ball Relax	Healthy	.019	.016	14
	Patient	.087	.112	15
	Total	.054	.087	29
Flexor Carpi Ulnaris in Rep 3 Ball Press	Healthy	.071	.080	14
	Patient	.179	.165	15
	Total	.127	.140	29
Flexor Carpi Ulnaris in Rep 3 Ball Relax	Healthy	.026	.035	14
	Patient	.085	.108	15
	Total	.057	.085	29

In the elbow flexion extension motion (EFE) within the comparison of healthy individuals and patients, the RMS mean of healthy individuals across the muscles was lower than

those of the patients. However, the extensor carpi ulnaris (ECU) muscle is the only one that showed significance between subjects with respect to health 0.021 ± 0.015 vs. 0.104 ± 0.159, p = 0.037. F (1, 27) = 4.836. This is shown in Graph A in Figure 4.1.

The higher RMS value in patients indicates that the muscle is being recruited with a higher demand than healthy individuals. Although the ECU is primarily a wrist moving muscle, its anatomy suggests it may play a role in elbow flexion. Due to the patients' injuries, neuromuscular coordination may be compromised leading the body to activate other nearby muscles to achieve the same motion.

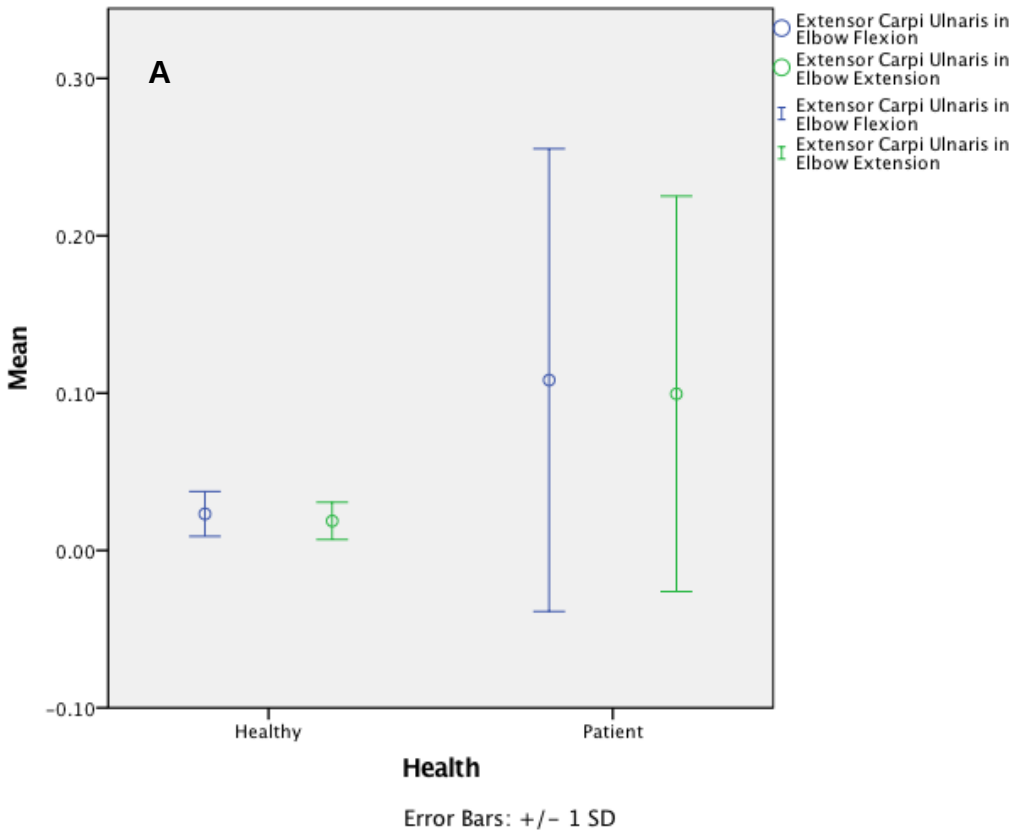


Figure 4.1 RMS means of ECU in EFE (A) motion in healthy individuals and patients with a standard deviation +/- 1

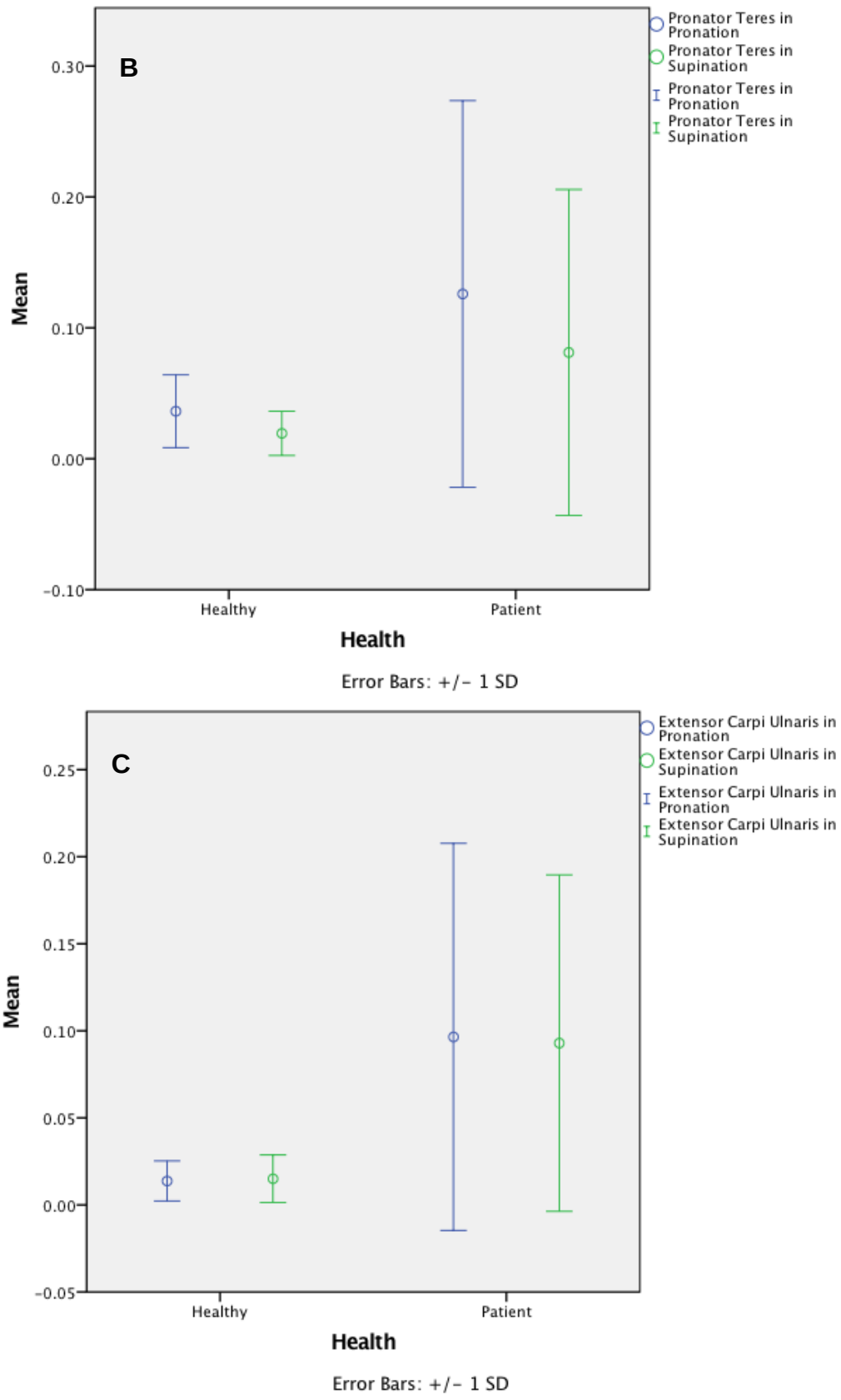


Figure 4.2 RMS means of PT in PS (B) and ECU in PS (C) motions in healthy individuals and patients with a standard deviation +/- 1

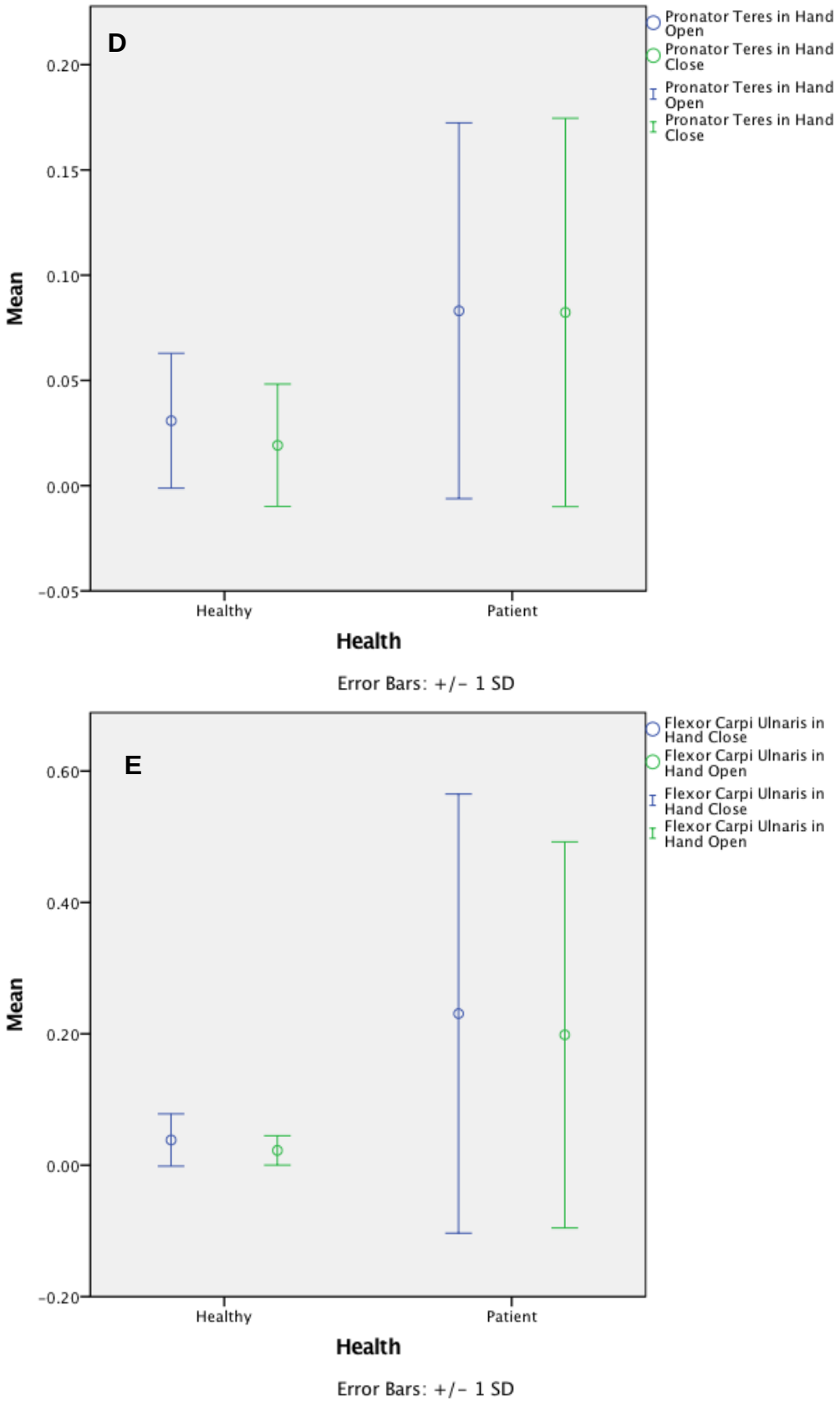


Figure 4.3. RMS means of PT in HOC (D) and FCU in HOC (E) motion in healthy individuals and patients with a standard deviation +/- 1

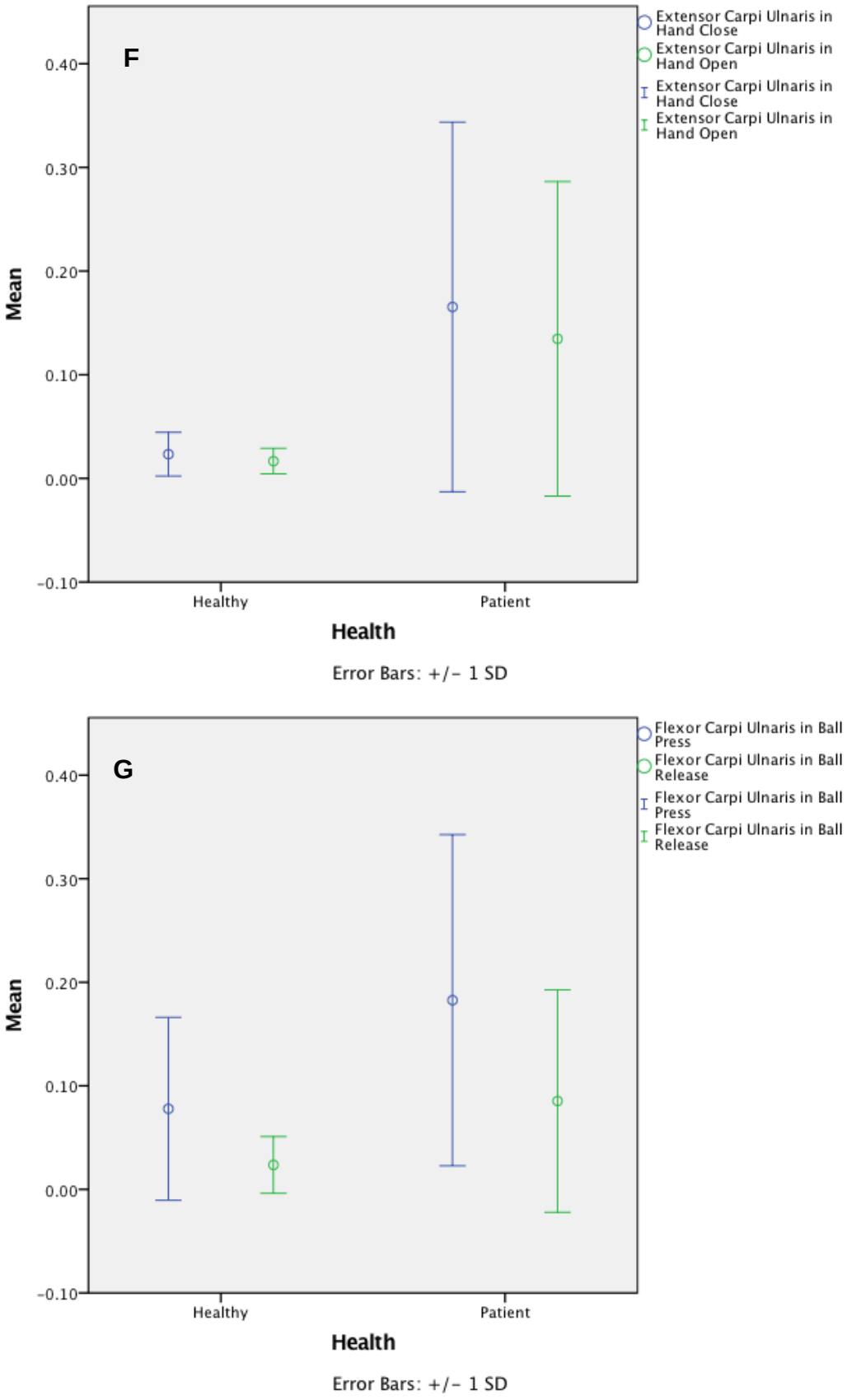


Figure 4.4. RMS means of ECU in HOC (F) and FCU in Ball Pressing (G) motion in healthy individuals and patients with a standard deviation +/- 1

In the pronation–supination motion, the healthy individuals' means were also lower than those of the patient population. Two muscles showed statistical significance in difference between healthy individuals and the patient population. The first muscle is the PT showing healthy individuals at 0.028 ± 0.046 vs. 0.103 ± 0.142, $p = 0.028$, $F(1,31) = 5.348$ (Graph B in Figure 4.2). The second muscle is the ECU showing healthy individuals at 0.015 ± 0.011 vs. 0.095 ± 0.1155, $p = 0.005$. $F(1,31) = 9.281$ (Graph C in Figure 4.2). As displayed in graph B in Figure 4.2, the PT is activated at a higher magnitude in patients than healthy individuals despite being the correct muscle to be activated in pronation. Due to the injuries and possible muscle atrophy, the body recruits a higher number of motor units to achieve the same motion as the healthy population. The ECU is not a primary mover in pronation and supination, however this muscle was over active in the patient population. Again, since the neuromuscular control may be compromised in the patients, over activation of non-required muscles is possible.

In the wrist flexion–extension motion, the mean of healthy individuals is lower than that of the patient average. However, none of the muscles showed statistical significance within this motion. Similarly, in the ulnar–radial deviation motion, the mean of healthy individuals is lower than that of the patient average. However, none of the muscles showed statistical significance within this motion. For further details, please see Table C.5 in Appendix C.

Just like the previous motion, the hand open–close motion also showed a general trend in the mean showing healthy individuals lower than the patient population. Conversely, in this motion, three muscles showed statistical significance. The first muscle was the PT with a healthy mean of 0.025 ± 0.032 vs. 0.083 ± 0.089, $p = 0.045$, $F(1,23) = 4.497$ (Graph D in Figure 4.3). Secondly, the FCU showed a healthy mean of 0.031 ± 0.035 vs. 0.215 ± 0.40, $p = 0.026$, $F(1,23) = 5.635$ (Graph E in Figure 4.3). Lastly, the ECU portrayed a healthy mean of 0.019 ± 0.021 vs. 0.15 ± 0.16, $p = 0.012$, $F(1,23) = 7.395$, 1 degree (Graph F in Figure 4.4).

The electrodes were directly placed on the muscles responsible for moving the fingers. Nevertheless, the forearm muscles are very tightly packed; therefore, the electrodes close to these muscles may have picked them up leading to the statistical significant differences obtained. The PT and the FCU are both near the flexor digitorum profundus, flexor digitorum superficialis, and palmaris longus, which are all flexors of the fingers.

Furthermore, the ECU is near the extensor digitorum muscle, which is responsible for extending the fingers. This could explain the differences in these muscles in the HOC motion.

Likewise, the ball pressing motion exhibited a general lower mean trend in healthy individuals compared to the patient population. This was only statistically significant in the FCU with a healthy mean of 0.051 ± 0.09 vs. 0.135 ± 0.156, p = 0.03, F (1,27) =5.281 (Graph G in Figure 4.4).

Next, the second type of analysis between early and late stage patients is reported and discussed (see Table 4.9, 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, and 4.21). A higher number of statistical significances were observed in this type of analysis.

Table 4.9. Pairwise comparison between patients at 0–1 months of injury and 4+ months of injury using RMS

Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0–1 Month	SE 4+ Months	Sig
EFE	TB	1.35	0.4	0.28	0.19	0.01
EFE	TB2	5.29	0.34	1.46	0.96	0.01
WFE	TB	0.90	0.11	0.19	0.10	0.002
PS	TB	0.86	0.14	0.24	0.14	0.014
PS	PT	0.05	0.20	0.06	0.03	0.04
URD	TB	5.38	0.12	1.59	1.42	0.022
URD	TB2	4.27	0.09	1.50	1.34	0.049
HOC	BB	0.25	0.08	0.06	0.04	0.035
HOC	TB	4.20	0.11	1.00	0.65	0.003
HOC	TB2	4.26	0.08	1.30	0.86	0.015
Ball	TB2	4.42	0.39	1.24	1.24	0.031
Ball	FCU	0.34	0.06	0.04	0.037	0.000026
Ball	ECU	0.02	0.44	0.13	0.13	0.032

Table 4.10. Pairwise comparison of TB in EFE motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Elbow Flexion	Healthy	.274	.297	13
	4+ months	.201	.108	6
	0-1 months	2.912	2.897	3
Triceps Long in Rep 1 in Elbow Extension	Healthy	.247	.213	13
	4+ months	.155	.096	6
	0-1 months	1.062	1.222	3
Triceps Long in Rep 2 in Elbow Flexion	Healthy	.250	.255	13
	4+ months	.192	.089	6
	0-1 months	1.094	1.382	3
Triceps Long in Rep 2 in Elbow Extension	Healthy	.214	.227	13
	4+ months	.164	.092	6
	0-1 months	1.051	1.199	3
Triceps Long in Rep 3 in Elbow Flexion	Healthy	.279	.309	13
	4+ months	.204	.105	6
	0-1 months	1.067	1.327	3
Triceps Long in Rep 3 in Elbow Extension	Healthy	.162	.084	13
	4+ months	.122	.063	6
	0-1 months	.936	.824	3

Table 4.11. Pairwise comparison of TB2 in EFE motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Elbow Flexion	Healthy	.055	.060	13
	4+ months	.366	.382	6
	0-1 months	5.270	8.880	3
Triceps Lateral in Rep 1 in Elbow Extension	Healthy	.069	.058	13
	4+ months	.403	.382	6
	0-1 months	5.199	8.760	3
Triceps Lateral in Rep 2 in Elbow Flexion	Healthy	.045	.038	13
	4+ months	.394	.389	6
	0-1 months	5.282	8.906	3
Triceps Lateral in Rep 2 in Elbow Extension	Healthy	.052	.041	13
	4+ months	.370	.401	6

	0-1 months	5.361	9.059	3
Triceps Lateral in Rep 3 in Elbow Flexion	Healthy	.072	.080	13
	4+ months	.427	.384	6
	0-1 months	5.296	8.928	3
Triceps Lateral in Rep 3 in Elbow Extension	Healthy	.066	.074	13
	4+ months	.358	.397	6
	0-1 months	5.358	9.107	3

Table 4.12. Pairwise comparison of TB2 in WFE motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Wrist Flexion	Healthy	.091	.117	13
	4+ Months	.103	.0867	7
	0-1 Months	1.01	1.245	2
Triceps Long in Rep 1 in Wrist Extension	Healthy	.092	.115	13
	4+ Months	.106	.0815	7
	0-1 Months	.992	1.234	2
Triceps Long in Rep 2 in Wrist Flexion	Healthy	.095	.116	13
	4+ Months	.109	.091	7
	0-1 Months	1.006	1.23	2
Triceps Long in Rep 2 in Wrist Extension	Healthy	.092	.114	13
	4+ Months	.108	.0881	7
	0-1 Months	.992	1.223	2
Triceps Long in Rep 3 in Wrist Flexion	Healthy	.096	.115	13
	4+ Months	.116	.101	7
	0-1 Months	.995	1.204	2
Triceps Long in Rep 3 in Wrist Extension	Healthy	.085	.068	13
	4+ Months	.092	.073	7
	0-1 Months	.407	.490	2

Table 4.13. Pairwise comparison of TB in PS motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Pronation	Healthy	.198	.517	16
	4+ Months	.127	.070	6
	0-1 Months	.955	1.252	2
Triceps Long in Rep 1 in Supination	Healthy	.133	.258	16
	4+ Months	.122	.044	6
	0-1 Months	.950	1.216	2
Triceps Long in Rep 2 in Pronation	Healthy	.126	.242	16
	4+ Months	.157	.051	6
	0-1 Months	.945	1.237	2
Triceps Long in Rep 2 in Supination	Healthy	.130	.241	16
	4+ Months	.137	.057	6
	0-1 Months	.945	1.237	2
Triceps Long in Rep 3 in Pronation	Healthy	.129	.244	16
	4+ Months	.152	.064	6
	0-1 Months	.950	1.245	2
Triceps Long in Rep 3 in Supination	Healthy	.089	.122	16
	4+ Months	.103	.057	6
	0-1 Months	.420	.481	2

Table 4.14. Pairwise comparison of PT in PS motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 in Pronation	Healthy	.046	.046	16
	4+ Months	.230	.191	6
	0-1 Months	.050	.028	2
Pronator Teres in Rep 1 in Supination	Healthy	.021	.019	16
	4+ Months	.165	.174	6
	0-1 Months	.035	.007	2
Pronator Teres in Rep 2 in Pronation	Healthy	.029	.024	16
	4+ Months	.240	.207	6
	0-1 Months	.060	.014	2
Pronator Teres in Rep 2 in Supination	Healthy	.019	.019	16
	4+ Months	.158	.186	6
	0-1 Months	.040	.014	2

Pronator Teres in Rep 3 in Pronation	Healthy	.033	.030	16
	4+ Months	.238	.210	6
	0-1 Months	.065	.007	2
	Total	.086	.123	30
Pronator Teres in Rep 3 in Supination	Healthy	.018	.014	16
	4+ Months	.173	.203	6
	0-1 Months	.050	.014	2

Table 4.15. Pairwise comparison of TB in URD motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Ulnar Deviation	Healthy	.104	.129	13
	4+ Months	.128	.100	5
	0-1 Months	6.243	10.387	4
Triceps Long in Rep 1 in Radial Deviation	Healthy	.102	.124	13
	4+ Months	.130	.101	5
	0-1 Months	5.850	9.533	4
Triceps Long in Rep 2 in Ulnar Deviation	Healthy	.105	.128	13
	4+ Months	.130	.109	5
	0-1 Months	6.295	10.453	4
Triceps Long in Rep 2 in Radial Deviation	Healthy	.104	.125	13
	4+ Months	.130	.107	5
	0-1 Months	6.128	10.088	4
Triceps Long in Rep 3 in Ulnar Deviation	Healthy	.105	.129	13
	4+ Months	.128	.0971	5
	0-1 Months	6.255	10.356	4
Triceps Long in Rep 3 in Radial Deviation	Healthy	.0831	.0616	13
	4+ Months	.0920	.0577	5
	0-1 Months	1.490	2.043	4

Table 4.16. Pairwise comparison of TB2 in URD motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Ulnar Deviation	Healthy	.029	.035	13
	4+ Months	.082	.091	5
	0-1 Months	4.285	8.324	4

Triceps Lateral in Rep 1 in Radial Deviation	Healthy	.028	.035	13
	4+ Months	.068	.086	5
	0-1 Months	4.245	8.251	4
Triceps Lateral in Rep 2 in Ulnar Deviation	Healthy	.030	.037	13
	4+ Months	.098	.093	5
	0-1 Months	4.258	8.269	4
Triceps Lateral in Rep 2 in Radial Deviation	Healthy	.029	.036	13
	4+ Months	.100	.089	5
	0-1 Months	4.290	8.334	4
Triceps Lateral in Rep 3 in Ulnar Deviation	Healthy	.029	.038	13
	4+ Months	.104	.105	5
	0-1 Months	4.285	8.337	4
Triceps Lateral in Rep 3 in Radial Deviation	Healthy	.030	.040	13
	4+ Months	.078	.091	5
	0-1 Months	4.248	8.262	4

Table 4.17. Pairwise comparison of BB in HOC motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Biceps in Rep 1 in Hand Open	Healthy	.085	.089	12
	4+ Months	.093	.066	7
	0-1 Months	.253	.202	3
Biceps in Rep 1 in Hand Close	Healthy	.083	.089	12
	4+ Months	.084	.055	7
	0-1 Months	.250	.203	3
Biceps in Rep 2 in Hand Open	Healthy	.088	.088	12
	4+ Months	.093	.065	7
	0-1 Months	.253	.202	3
Biceps in Rep 2 in Hand Close	Healthy	.084	.089	12
	4+ Months	.087	.064	7
	0-1 Months	.260	.207	3
Biceps in Rep 3 in Hand Open	Healthy	.086	.089	12
	4+ Months	.093	.064	7
	0-1 Months	.253	.202	3
Biceps in Rep 3 in Hand Close	Healthy	.083	.087	12
	4+ Months	.086	.054	7
	0-1 Months	.250	.207	3

Table 4.18. Pairwise comparison of TB in HOC motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Hand Open	Healthy	.124	.141	12
	4+ Months	.123	.164	7
	0-1 Months	4.843	6.376	3
Triceps Long in Rep 1 in Hand Close	Healthy	.121	.142	12
	4+ Months	.119	.162	7
	0-1 Months	4.883	6.444	3
Triceps Long in Rep 2 in Hand Open	Healthy	.128	.142	12
	4+ Months	.126	.159	7
	0-1 Months	4.877	6.441	3
Triceps Long in Rep 2 in Hand Close	Healthy	.123	.144	12
	4+ Months	.121	.170	7
	0-1 Months	4.467	5.721	3
Triceps Long in Rep 3 in Hand Open	Healthy	.128	.147	12
	4+ Months	.120	.166	7
	0-1 Months	4.917	6.453	3
Triceps Long in Rep 3 in Hand Close	Healthy	.094	.062	12
	4+ Months	.071	.048	7
	0-1 Months	1.227	1.320	3

Table 4.19. Pairwise comparison of TB2 in HOC motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Hand Open	Healthy	.051	.092	12
	4+ Months	.067	.061	7
	0-1 Months	4.267	7.182	3
Triceps Lateral in Rep 3 in Hand Close	Healthy	.049	.090	12
	4+ Months	.069	.062	7
	0-1 Months	4.277	7.200	3
Triceps Lateral in Rep 1 in Hand Open	Healthy	.051	.092	12
	4+ Months	.084	.062	7
	0-1 Months	4.257	7.174	3
Triceps Lateral in Rep 3 in Hand Close	Healthy	.051	.093	12
	4+ Months	.071	.061	7

	0-1 Months	4.270	7.188	3
Triceps Lateral in Rep 1 in Hand Open	Healthy	.051	.095	12
	4+ Months	.087	.064	7
	0-1 Months	4.250	7.153	3
Triceps Lateral in Rep 3 in Hand Close	Healthy	.058	.115	12
	4+ Months	.080	.069	7
	0-1 Months	4.257	7.165	3

Table 4.20. Pairwise comparison of TB2 in Ball Press motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Ball Press	Healthy	.269	.204	14
	4+ Months	.693	.501	3
	0-1 Months	4.427	7.373	3
Triceps Lateral in Rep 1 in Ball Relax	Healthy	.118	.142	14
	4+ Months	.437	.562	3
	0-1 Months	4.417	7.555	3
Triceps Lateral in Rep 2 in Ball Press	Healthy	.306	.210	14
	4+ Months	.373	.309	3
	0-1 Months	4.427	7.391	3
Triceps Lateral in Rep 2 in Ball Relax	Healthy	.091	.123	14
	4+ Months	.090	.089	3
	0-1 Months	4.447	7.607	3
Triceps Lateral in Rep 3 in Ball Press	Healthy	.298	.208	14
	4+ Months	.650	.372	3
	0-1 Months	4.460	7.431	3
Triceps Lateral in Rep 3 in Ball Relax	Healthy	.096	.131	14
	4+ Months	.083	.085	3
	0-1 Months	4.317	7.347	3

Table 4.21. Pairwise comparison of FCU in Ball Press motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Flexor Carpi Ulnaris in Rep 1 in Ball Press	Healthy	.084	.094	14
	4+ Months	.087	.058	3
	0-1 Months	.413	.140	3

Flexor Carpi Ulnaris in Rep 1 in Ball Relax	Healthy	.028	.041	14
	4+ Months	.027	.006	3
	0-1 Months	.253	.133	3
Flexor Carpi Ulnaris in Rep 2 in Ball Press	Healthy	.080	.093	14
	4+ Months	.117	.085	3
	0-1 Months	.420	.165	3
Flexor Carpi Ulnaris in Rep 2 in Ball Relax	Healthy	.019	.016	14
	4+ Months	.030	.010	3
	0-1 Months	.260	.140	3
Flexor Carpi Ulnaris in Rep 3 in Ball Press	Healthy	.071	.080	14
	4+ Months	.093	.064	3
	0-1 Months	.427	.176	3
Flexor Carpi Ulnaris in Rep 3 in Ball Relax	Healthy	.026	.035	14
	4+ Months	.030	.010	3
	0-1 Months	.237	.165	3

Table 4.22. Pairwise comparison of ECU in Ball Press motion between patients at 0–1 months of injury and 4+ months of injury using RMS

	Health	Mean	Std. Deviation	N
Extensor Carpi Ulnaris in Rep 1 in Ball Press	Healthy	.026	.030	14
	4+ Months	.433	.632	3
	0-1 Months	.023	.006	3
Extensor Carpi Ulnaris in Rep 1 in Ball Relax	Healthy	.016	.014	14
	4+ Months	.410	.608	3
	0-1 Months	.017	.006	3
Extensor Carpi Ulnaris in Rep 2 in Ball Press	Healthy	.025	.026	14
	4+ Months	.453	.667	3
	0-1 Months	.020	.000	3
Extensor Carpi Ulnaris in Rep 2 in Ball Relax	Healthy	.015	.014	14
	4+ Months	.420	.626	3
	0-1 Months	.020	.010	3
Extensor Carpi Ulnaris in Rep 3 in Ball Press	Healthy	.026	.029	14
	4+ Months	.463	.692	3
	0-1 Months	.023	.006	3
Extensor Carpi Ulnaris in Rep 3 in Ball Relax	Healthy	.014	.011	14
	4+ Months	.430	.659	3
	0-1 Months	.027	.012	3

Both long and lateral heads of the triceps had a higher mean in the EFE movement in patients at their first month of therapy compared to patients in their 4th month 0.35 ± 2.9 vs. 0.4 ± 0.85, p = 0.01 (see Graphs A and B in Figures 4.5 and 4.6) This shows that healthier individuals tend to depend more on gravity to obtain elbow extension while patients have to actively contract their triceps at a great extent to obtain the movement required. In wrist flexion and extension, the long head of the triceps also exhibited higher activation levels in the 0–1 month rehabilitation population 0.90 ± 0.09 vs. 0.11±1.24, p = 0.002 (Graph C in Figure 4.6). The long head is responsible for extending the elbow and adducting the shoulder. The injury may cause the patients to actively stimulate the muscle in order to keep the arm stable at a 90-degree angle when they are performing the wrist motions. Moreover, subjects were asked to keep their arm to their side at all times. This could be effortless for healthy individuals, while patients with fresh injuries have uncoordinated neuromuscular control leading to the over-activation observed.

Similarly, in the pronation and supination motion, the long head of the triceps showed almost the same mean difference as shown in the wrist flexion–extension motion with a 0–1 month mean of 0.86 ± 0.07 vs. 0.14 ± 1.25, p = 0.014 (Graph D in Figure 4.7). Again, this could be related to stabilizing the elbow at 90 degrees and keeping the arm close to the body. In contrast, the PT displayed a higher mean in patients towards the end of their therapy compared to those in the beginning 0.05 ± 0.03 vs. 0.20 ± 0.19, p = 0.04 (Graph E in Figure 4.7). This finding does not align with the trend of higher means in first-month patients. Nevertheless, it could be explained by the incapability of contracting the muscle by patients, and therefore, it does not show high levels of activation.

Again, in the URD (Graphs F and G in Figure 4.8) and HOC (Graph H and I in Figure 4.9) movement, both TB and TB2 in URD showed statistical differences of 5.38 ± 0.1 vs. 1.59 ± 0.051, p = 0.022 and 4.27 ± 0.09 vs. 1.50 ± 8.2, p = 0.49 respectively. They could be explained by the previous explanations in WFE and PS. In addition to the TB and TB2 showing differences in HOC (Graphs J and K in Figure 4.10), 4.2 ± 0.1 vs. 1.00 ± 0.016, p = 0.003 and 4.26 ± 7.18 vs. 0.08 ± 0.06, p = 0.015, the biceps showed a higher mean in 0–1 month patients versus the 4+ months patients 0.25 ± 0.11 vs. 0.08 ± 0.06, p = 0.022 (Graph I in Figure 4.9). The biceps should be activated enough to stabilize the elbow in place, however it seemed to activate even when the 0–1 months individuals

closed their hand. This is another example showing neuromuscular control being compromised enough to cause inappropriate activations of muscles.

In the ball pressing motion, 3 muscles showed significant differences. Firstly, the lateral head of the triceps showed a mean of 4.42 ± 0.5 vs. 0.39 ± 7.37, p = 0.031 (Graph L in Figure 4.11). The activation of this muscle is normal in this case, as the motion requires elbow extension. The higher magnitude of activation in the 0–1 patient group is the common trend and therefore aligns with the findings previously mentioned in this thesis explaining that injured people may require higher activation to achieve the same output as healthier individuals. Next, the FCU also showed a much greater mean then the late stage rehabilitation patients 0.34 ± 0.14 vs. 0.06 ± 0.056, p = 0.000026 (Graph M in Figure 4.11). Although the wrist should not have moved much, it is possible that some individuals used their wrist flexors to stabilize their hand on top of the ball thus showing these differences between the groups. Lastly, the ECU showed noteworthy differences in the mean 0.02 ± 0.006 vs. 0.44 ± 0.63, p = 0.032 (Graph N in Figure 4.12). Unlike the general trend of higher mean in the first group of patients, the ECU depicted a much larger mean in the later group than the early group. This is very unusual as the ECU is a wrist extensor and the wrist was not extended at any point. Conversely, the anatomical origin of the ECU suggests it may play a role in elbow motion. This may be the reason this difference is observed. The incoordination of muscle activation is no longer contracting the muscles that will expend the least energy in the movement but it appears that the body will contract whichever muscle it can contract.

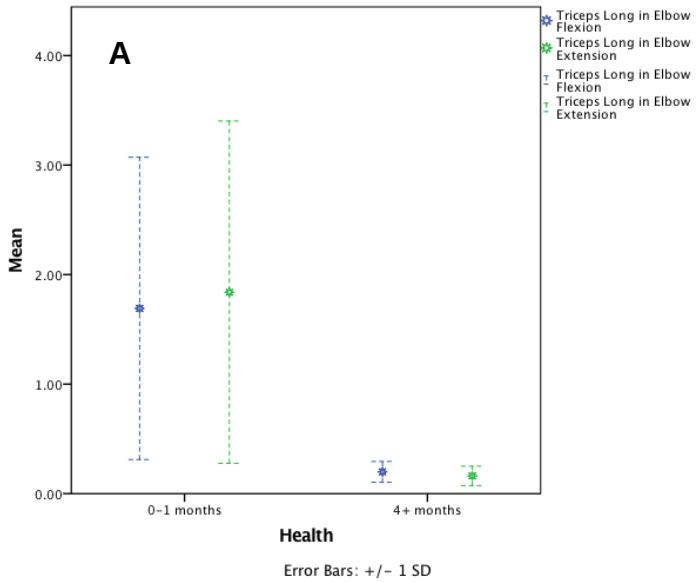


Figure 4.5. RMS means of TB in EFE (A) in early patient group and late patient group with a standard deviation +/- 1

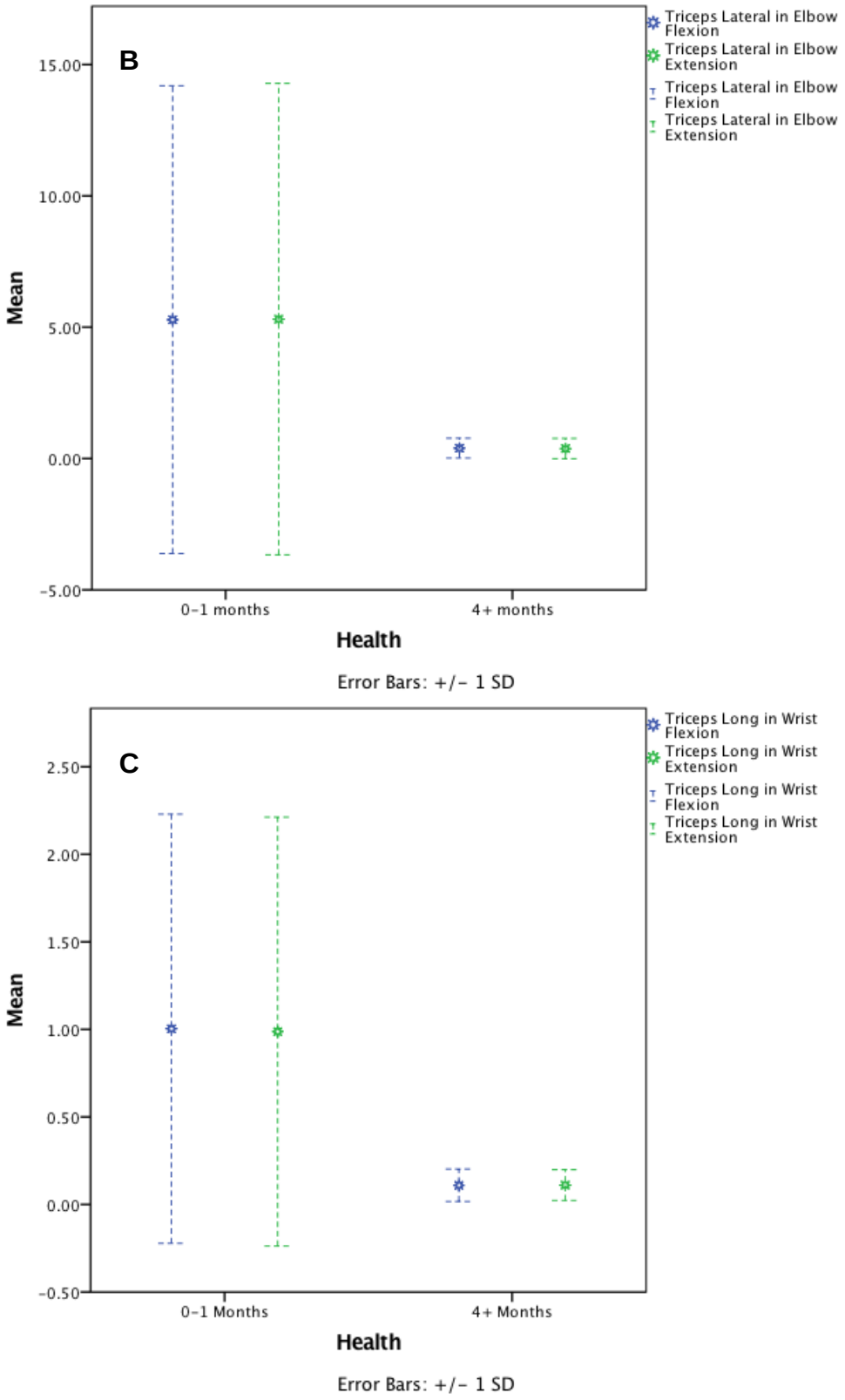


Figure 4.6. RMS means of TB2 in EFE (B) and TB in WFE (C) motions in early patient group and late patient group with a standard deviation +/- 1

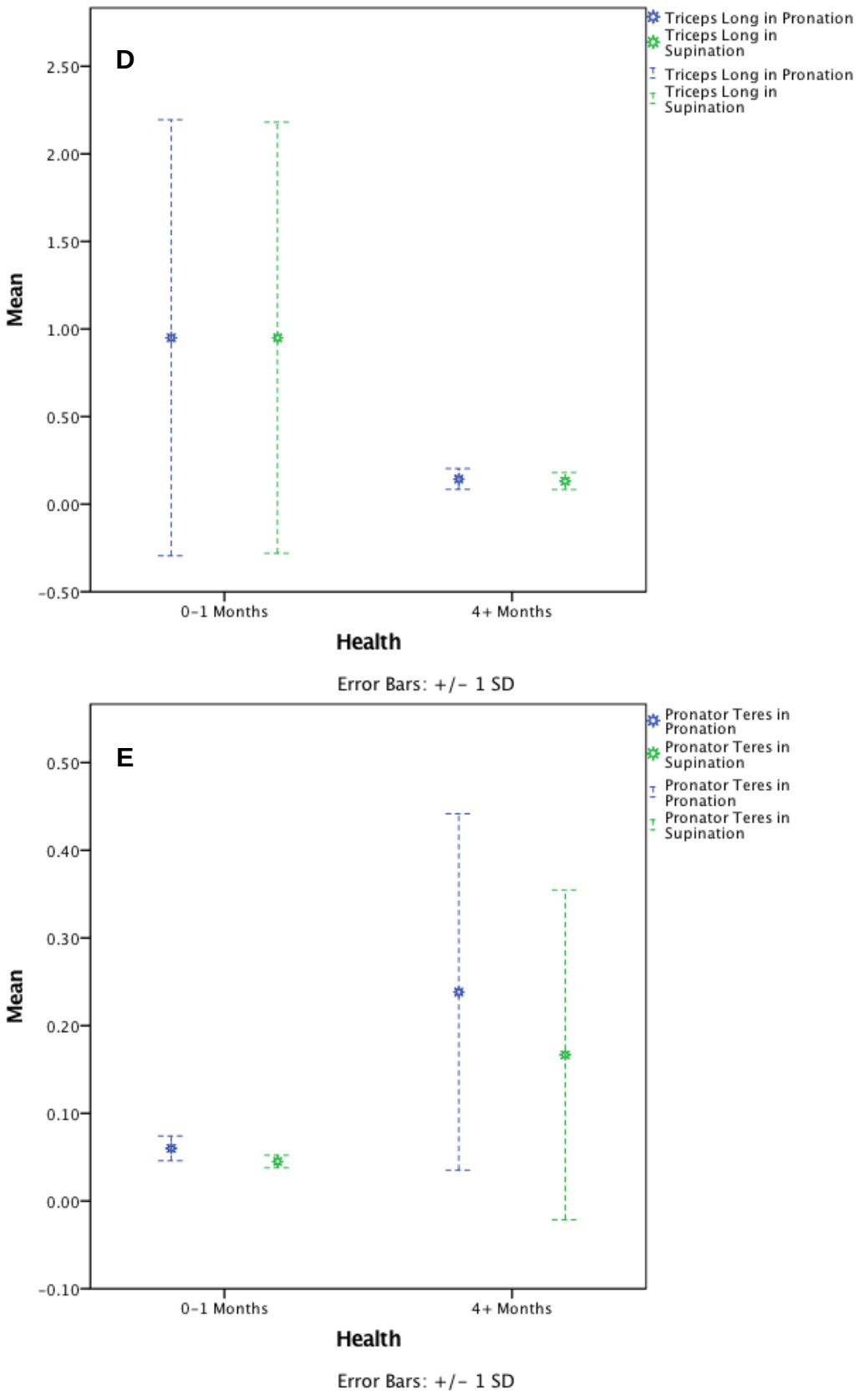


Figure 4.7. RMS means of TB in PS (D) and PT in PS (E) motions in early patient group and late patient group with a standard deviation +/- 1

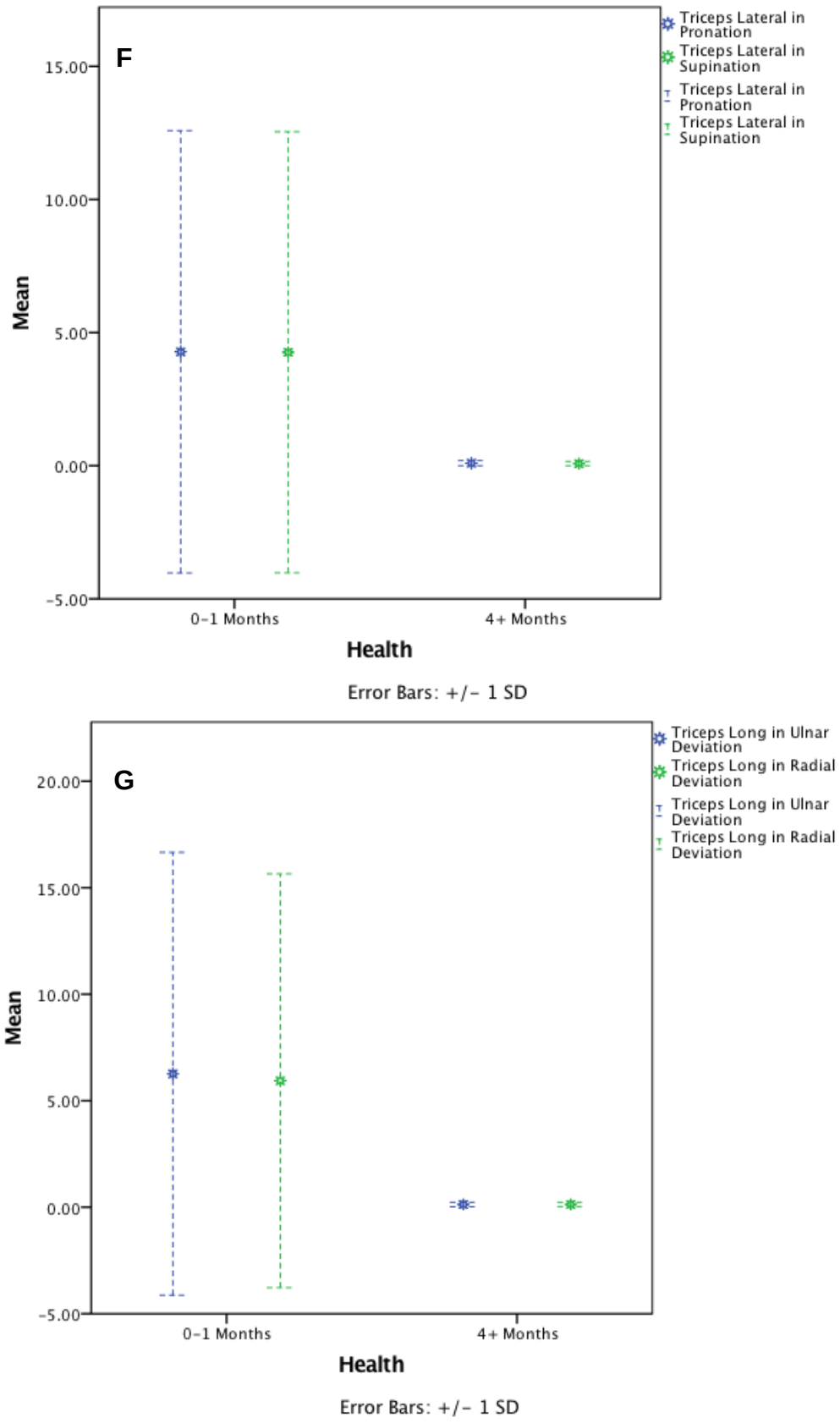


Figure 4.8. RMS means of TB2 in PS (F) and TB in URD (G) motions in early patient group and late patient group with a standard deviation +/- 1

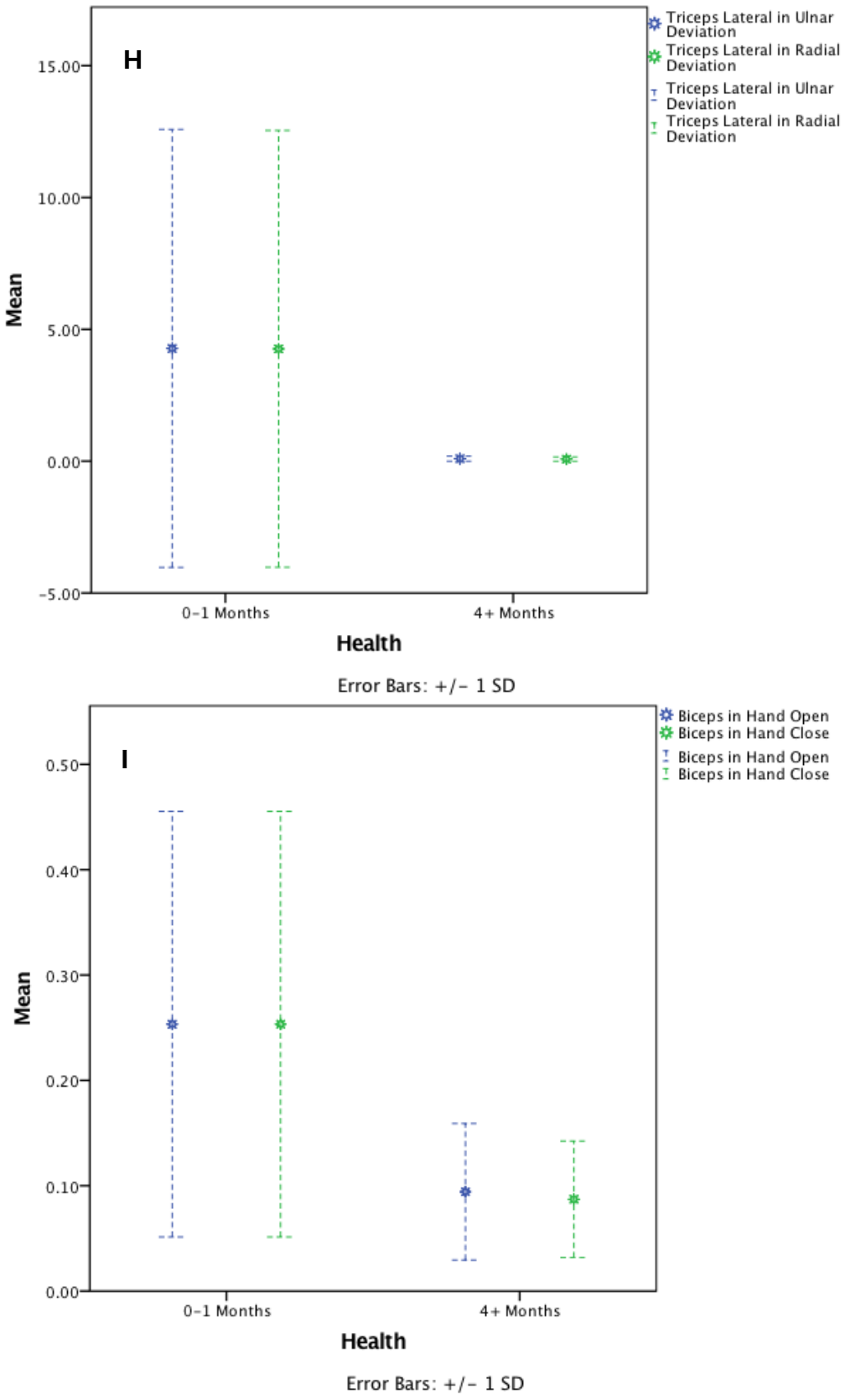


Figure 4.9. RMS means of TB2 in URD (H) and BB in HOC (I) motions in early patient group and late patient group with a standard deviation +/- 1

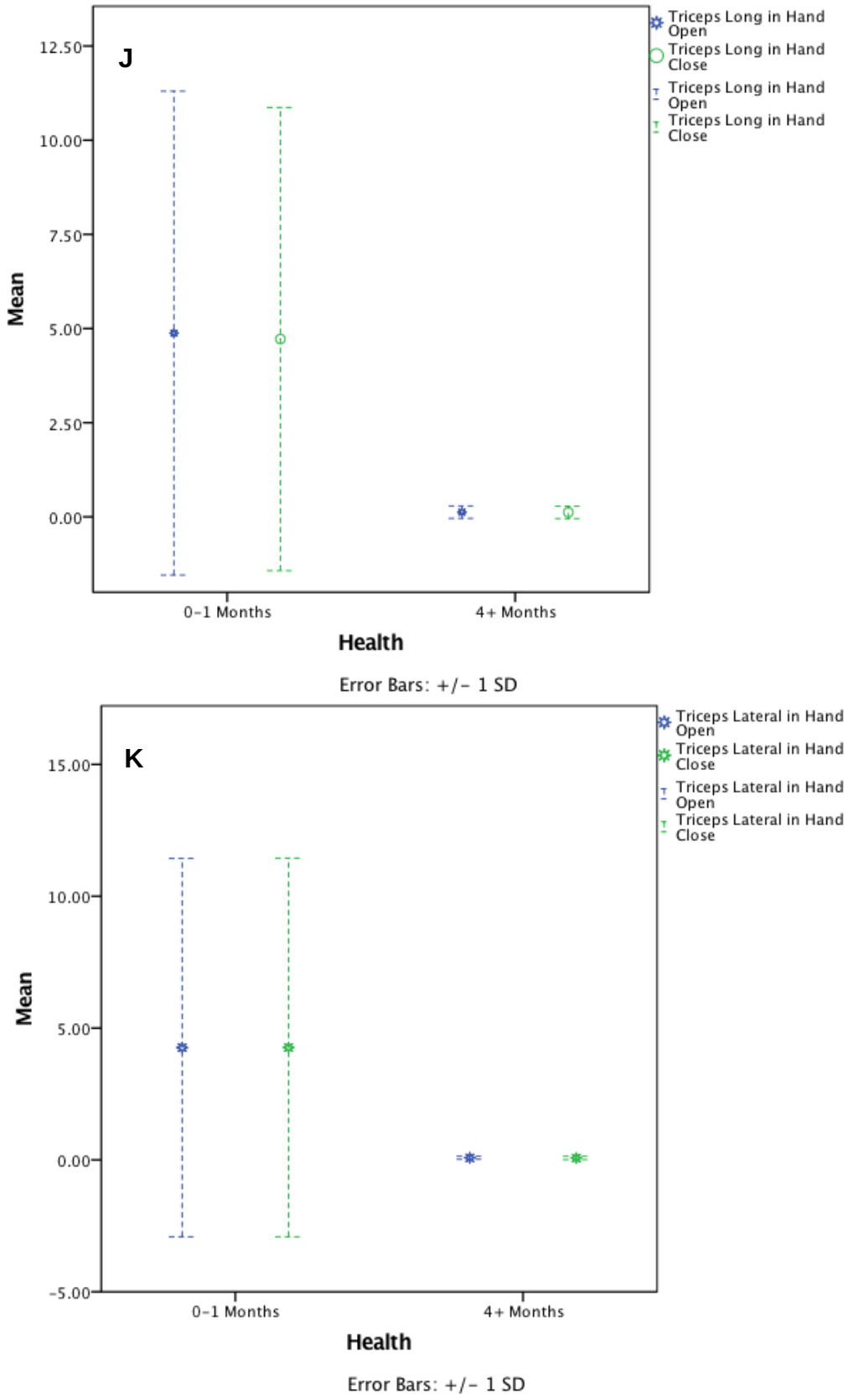


Figure 4.10. RMS means of TB in HOC (J) and TB2 in HOC (K) motions in early patient group and late patient group with a standard deviation +/- 1

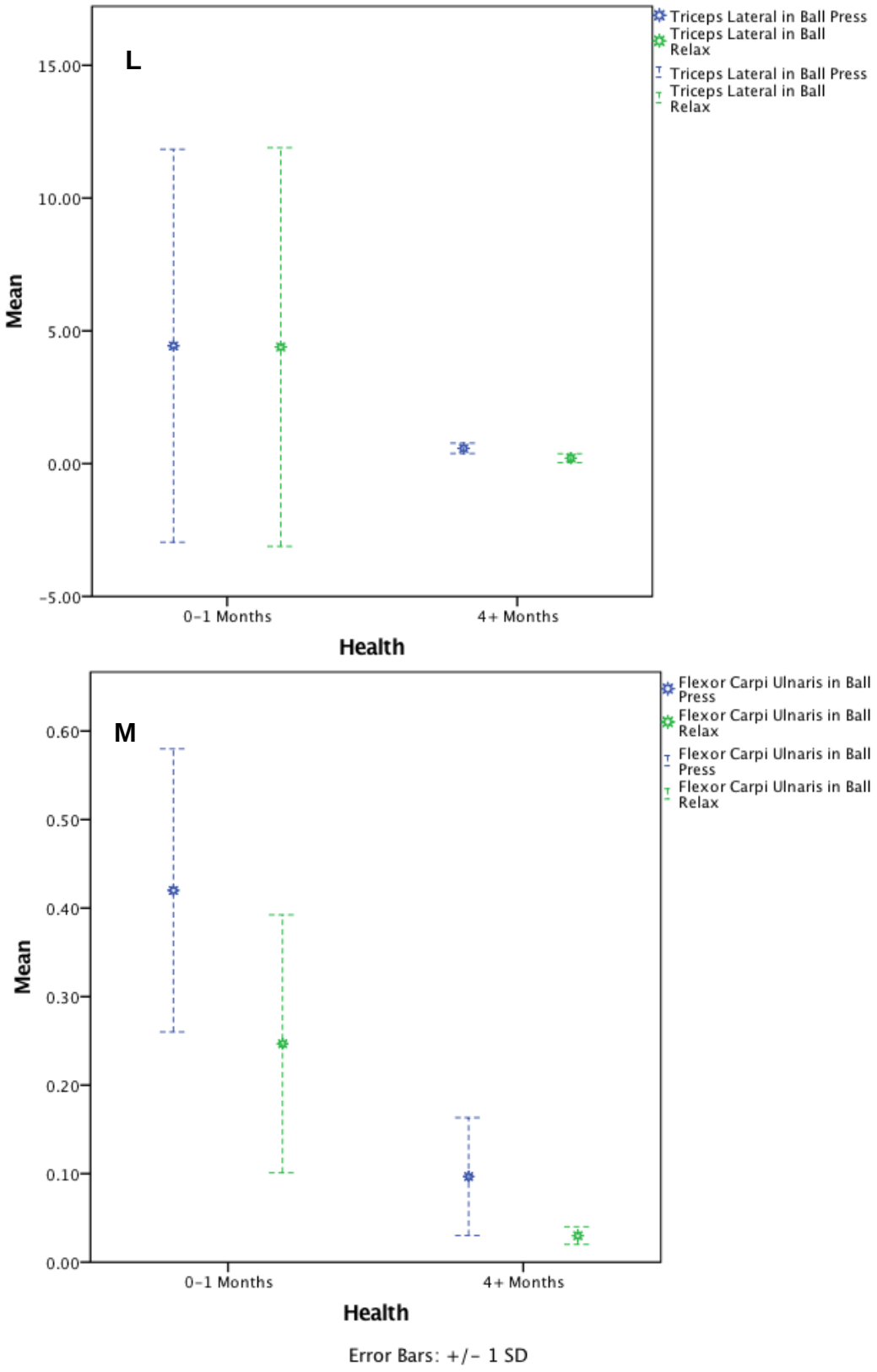


Figure 4.11. RMS means of TB2 in Ball Press (L) and FCU in Ball Press (M) motions in early patient group and late patient group with a standard deviation

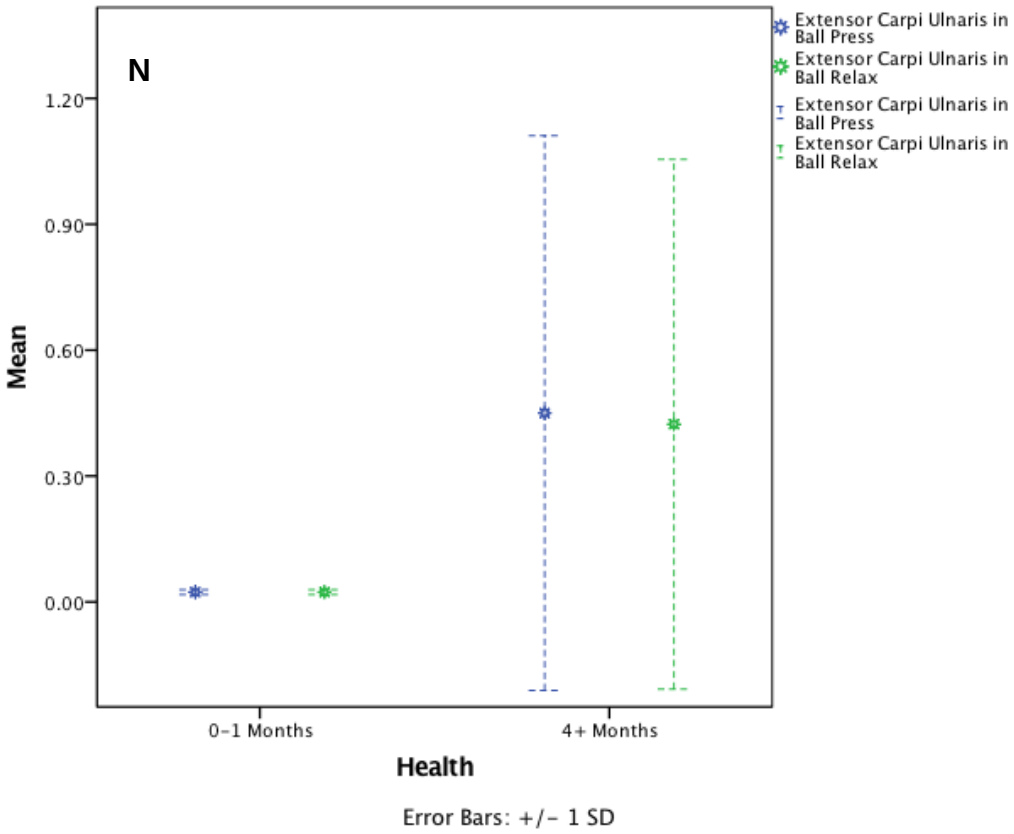


Figure 4.12. RMS mean of ECU in Ball Press (L) motion in early patient group and late patient group with a standard deviation +/- 1

4.2 Average Rectified Signal

The next section will report the results of the ARV in a comparison of healthy individuals versus patients and within the patient population in the early rehabilitation group and the late stage rehabilitation group. Table 4.23, 4.24, 4.25, and 4.26 below portray the result of the first analysis.

Table 4.23. Statistical analysis comparing healthy individuals to patients using ARV

Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
PS	ECU	-0.005	-0.036	0.006	0.006	0.001	12.545
WFE	ECU	-0.002	-0.018	0.004	0.005	0.019	6.426

Ball	TB	-0.006	0.079	0.027	0.027	0.036	4.88

Table 4.24. Statistical analysis of ECU in PS motion within each repetition comparing healthy individuals to patients using ARV

	Health	Mean	Std. Deviation	N
Extensor Carpi Ulnaris in Rep 1 in Pronation	Healthy	-.004	.006	16
	Patient	-.031	.034	14
	Total	-.017	.027	30
Extensor Carpi Ulnaris in Rep 1 in Supination	Healthy	-.004	.006	16
	Patient	-.031	.034	14
	Total	-.017	.027	30
Extensor Carpi Ulnaris in Rep 2 in Pronation	Healthy	-.005	.006	16
	Patient	-.039	.036	14
	Total	-.021	.030	30
Extensor Carpi Ulnaris in Rep 2 in Supination	Healthy	-.004	.006	16
	Patient	-.037	.033	14
	Total	-.020	.028	30
Extensor Carpi Ulnaris in Rep 3 in Pronation	Healthy	-.005	.006	16
	Patient	-.039	.036	14
	Total	-.021	.030	30
Extensor Carpi Ulnaris in Rep 3 in Supination	Healthy	-.005	.006	16
	Patient	-.037	.037	14
	Total	-.020	.030	30

Table 4.25. Statistical analysis of ECU in WFE motion within each repetition comparing healthy individuals to patients using ARV

	Health	Mean	Std. Deviation	N
Extensor Carpi Ulnaris in Rep 1 in Wrist Flexion	Healthy	-.002	.014	14
	Patient	-.018	.020	11
	Total	-.009	.018	25
Extensor Carpi Ulnaris in Rep 1 in Wrist Extension	Healthy	-.003	.014	14
	Patient	-.018	.020	11
	Total	-.010	.018	25
Extensor Carpi Ulnaris in Rep 2 in Wrist Flexion	Healthy	-.001	.013	14
	Patient	-.021	.022	11

	Total	-.010	.020	25
Extensor Carpi Ulnaris Rep 2 in Wrist Extension	Healthy	-.002	.014	14
	Patient	-.020	.021	11
	Total	-.010	.019	25
Extensor Carpi Ulnaris in Rep 3 in Wrist Flexion	Healthy	-.002	.014	14
	Patient	-.015	.015	11
	Total	-.008	.015	25
Extensor Carpi Ulnaris Rep 3 in Wrist Extension	Healthy	-.002	.013	14
	Patient	-.018	.018	11
	Total	-.009	.017	25

Table 4.26. Statistical analysis of TB in Ball Press motion within each repetition comparing healthy individuals to patients using ARV

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Ball Press	Healthy	-.025	.116	14
	Patient	.077	.107	15
	Total	.028	.121	29
Triceps Long in Rep 1 in Ball Relax	Healthy	-.027	.129	14
	Patient	.075	.100	15
	Total	.026	.124	29
Triceps Long in Rep 2 in Ball Press	Healthy	-.029	.119	14
	Patient	.077	.107	15
	Total	.026	.123	29
Triceps Long in Rep 2 in Ball Relax	Healthy	-.026	.128	14
	Patient	.077	.119	15
	Total	.027	.132	29
Triceps Long in Rep 3 in Ball Press	Healthy	-.027	.116	14
	Patient	.079	.104	15
	Total	.028	.121	29
Triceps Long in Rep 3 in Ball Relax	Healthy	.101	.065	14
	Patient	.089	.087	15
	Total	.094	.076	29

Statistical significances were observed in the ARV metric during three instances between the general healthy population and the patient population. The first two instances were in the ECU during pronation and supination with a healthy mean of 0.005 ± 0.00629 vs. 0.036 ± 0.03416, p = 0.001, F (1,28) = 12.545 (Graph A in Figure 4.13) and during WFE healthy mean 0.002 ± 0.004 vs. -0.018 ± 0.005, p = 0.019, F (1,23) = 6.426 (Graph B in Figure 4.14). The ECU is not responsible for pronation or supination; however, it showed higher levels of activation, which leads to the same possible conclusion: a compromised neuromuscular system causes contractions in unrequired muscles. In contrast, the ECU is a required muscle in the ulnar and radial deviation motion. The higher mean simply aligns with the previously mentioned observation in the trend of higher means in patients when compared to healthy individuals. Lastly, a significant difference was portrayed in the ball pressing action showing a healthy mean of the long head of the triceps at 0.006 ± 0.11621 vs. 0.079 ± 0.10694, p = 0.036, F (1,27) = 4.88 (Graph C in Figure 4.14). This also supports the statement showing patients requiring extra activation to achieve the same motion as healthy individuals.

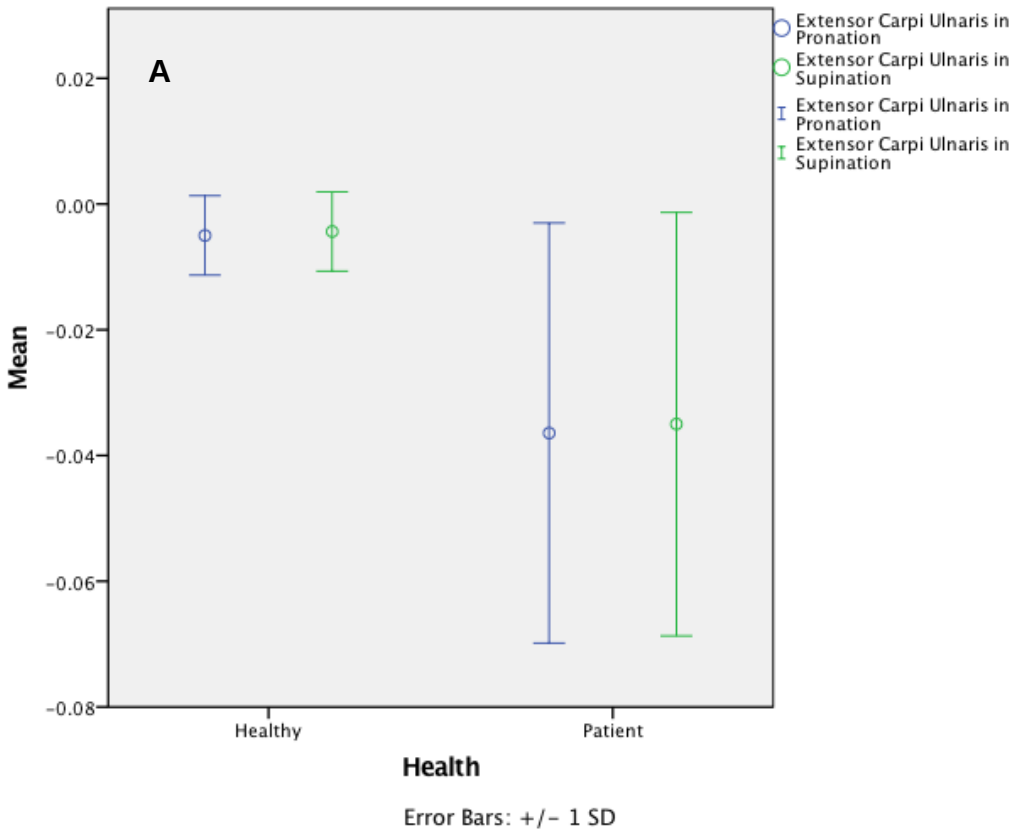


Figure 4.13. ARV mean of ECU in PS (A) motion in healthy individuals and patients with a standard deviation +/- 1

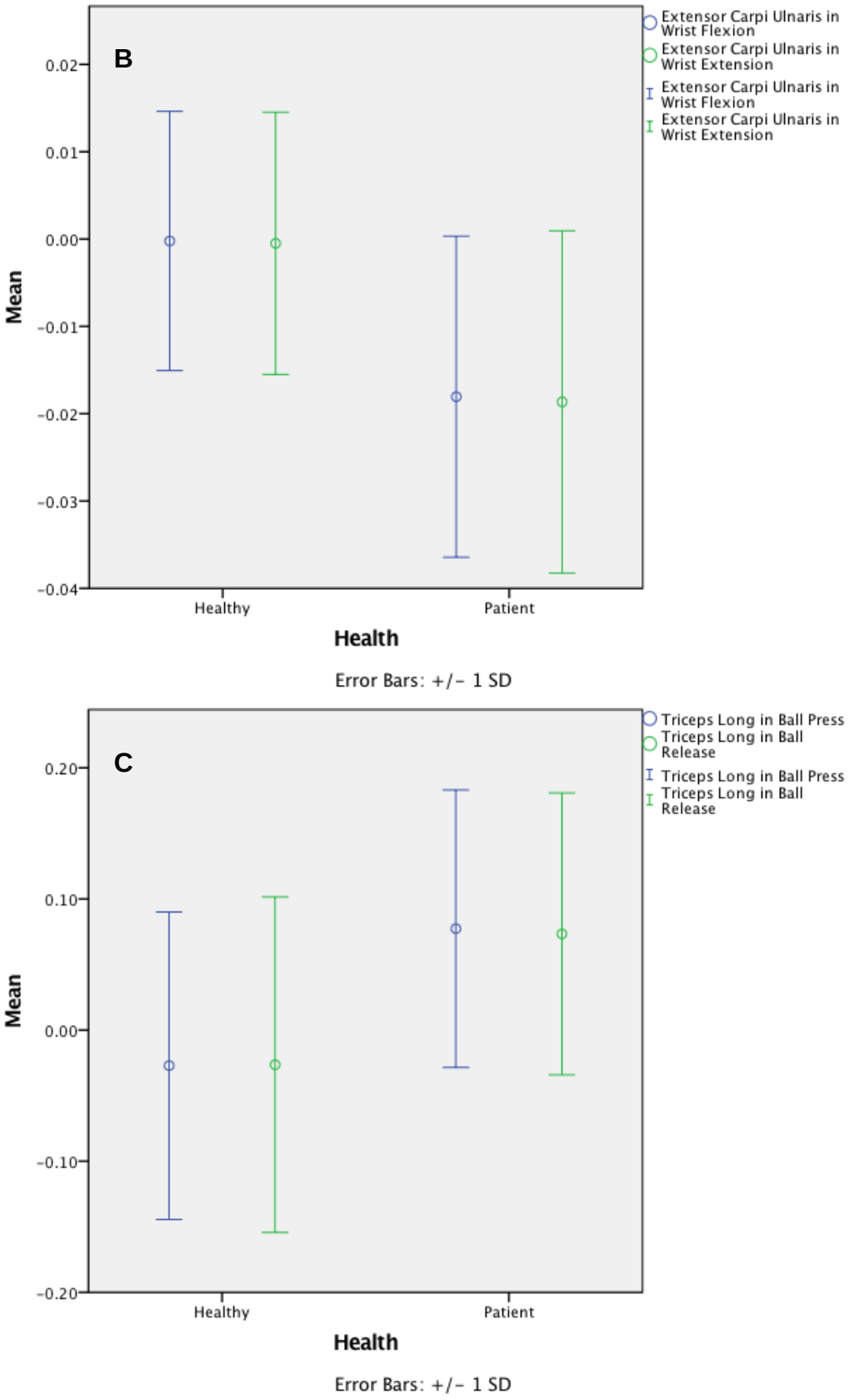


Figure 4.14. ARV means of ECU in WFE (B) and TB in Ball Pressing (C) motions in healthy individuals and patients with a standard deviation +/- 1

As mentioned earlier, further analysis was done by comparing patients at the start of their therapy (first month post surgery or injury) to those towards the end (4 months post surgery or injury). This is shown in Table 4.27, 4.28, 4.29, 4.30, 4.31, 4.32, 4.33, 4.34, 4.35, 4.36, 4.37, 4.38, 4.39, 4.40, and 4.41. Just like RMS, a higher number of statistical significances were observed in this type of analysis as well. Moreover, most of the differences observed in RMS are also observed in ARV.

Table 4.27 Pairwise comparison between patients at 0–1 months of injury and 4+ months of injury using ARV

Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0–1 Month	SE 4+ Months	Sig.
EFE	TB	0.72	-0.017	0.151198	0.106913	0.001
EFE	TB2	-3.42	-0.25	0.998956	0.706369	0.016
EFE	ECU	-0.04	-0.004	0.008534	0.006035	0.017
PS	TB	0.39	-0.001	0.136510	0.096527	0.029
WFE	TB	0.71	-0.02	0.159137	0.112527	0.001
WFE	TB2	-3.5	-0.07	1.025719	0.725293	0.012
URD	TB	-4.3	-0.03	1.362541	1.218694	0.03
URD	ECU	0.68	-0.02	0.237164	0.212126	0.036
HOC	TB	2.3	-0.02	0.492705	0.322551	0.001
HOC	TB2	-2.84	0.016	0.892079	0.584003	0.014
BALL	TB2	1.53	0.014	0.767844	1.172901	0.001
BALL	PT	-0.008	0.06	0.012209	0.018650	0.005
BALL	FCU	-0.09	0.002	0.032452	0.049571	0.002

Table 4.28. Pairwise comparison of TB in EFE motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Elbow Flexion	Healthy	.053	.184	15
	4+ Months	-.043	.082	6
	0-1 Month	.570	1.076	3
Triceps Long in Rep 1 in Elbow Extension	Healthy	.066	.190	15
	4+ Months	-.032	.085	6
	0-1 Month	.747	.955	3
Triceps Long in Rep 2 in Elbow Flexion	Healthy	.062	.181	15
	4+ Months	-.045	.079	6
	0-1 Month	.758	.943	3

Triceps Long in Rep 2 in Elbow Extension	Healthy	.061	.196	15
	4+ Months	-.038	.088	6
	0-1 Month	.742	.942	3
Triceps Long in Rep 3 in Elbow Flexion	Healthy	.049	.196	15
	4+ Months	-.045	.081	6
	0-1 Month	.782	.939	3
Triceps Long in Rep 3 in Elbow Extension	Healthy	.139	.125	15
	4+ Months	.098	.067	6
	0-1 Month	.731	.774	3

Table 4.29. Pairwise comparison of TB2 in EFE motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	**Mean**	**Std. Deviation**	**N**
Triceps Lateral in Rep 1 in Elbow Flexion	Healthy	-.015	.036	15
	4+ Months	-.248	.434	6
	0-1 Month	-3.424	6.080	3
Triceps Lateral in Rep 1 in Elbow Extension	Healthy	-.012	.035	15
	4+ Months	-.255	.436	6
	0-1 Month	-3.228	5.763	3
Triceps Lateral in Rep 1 in Elbow Flexion	Healthy	-.012	.037	15
	4+ Months	-.258	.436	6
	0-1 Month	-3.438	6.117	3
Triceps Lateral in Rep 1 in Elbow Extension	Healthy	-.012	.031	15
	4+ Months	-.259	.436	6
	0-1 Month	-3.371	5.999	3
Triceps Lateral in Rep 1 in Elbow Flexion	Healthy	-.014	.035	15
	4+ Months	-.260	.433	6
	0-1 Month	-3.563	6.348	3
Triceps Lateral in Rep 1 in Elbow Extension	Healthy	-.015	.031	15
	4+ Months	-.253	.438	6
	0-1 Month	-3.500	6.160	3

Table 4.30. Pairwise comparison of ECU in EFE motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Extensor Carpi Ulnaris in Rep 1 in Elbow Flexion	Healthy	-.004	.012	15
	4+ Months	.000	.009	6
	0-1 Month	-.037	.023	3
Extensor Carpi Ulnaris in Rep 1 in Elbow Extension	Healthy	-.004	.012	15
	4+ Months	-.001	.009	6
	0-1 Month	-.023	.052	3
Extensor Carpi Ulnaris in Rep 2 in Elbow Flexion	Healthy	-.003	.013	15
	4+ Months	-.004	.016	6
	0-1 Month	-.033	.028	3
Extensor Carpi Ulnaris in Rep 2 in Elbow Extension	Healthy	-.004	.012	15
	4+ Months	-.007	.014	6
	0-1 Month	-.020	.046	3
Extensor Carpi Ulnaris in Rep 3 in Elbow Flexion	Healthy	-.004	.012	15
	4+ Months	-.009	.014	6
	0-1 Month	-.031	.026	3
Extensor Carpi Ulnaris in Rep 3 in Elbow Extension	Healthy	-.004	.012	15
	4+ Months	-.003	.011	6
	0-1 Month	-.039	.033	3

Table 4.31. Pairwise comparison of PT in PS motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Pronation	Healthy	-.028	.073	16
	4+ Months	-.017	.073	6
	0-1 Months	.427	.670	3
Triceps Long in Rep 1 in Supination	Healthy	-.082	.258	16
	4+ Months	-.017	.074	6
	0-1 Months	.423	.664	3
Triceps Long in Rep 2 in Pronation	Healthy	-.079	.244	16
	4+ Months	-.017	.074	6
	0-1 Months	.433	.681	3
Triceps Long in Rep 2 in Supination	Healthy	-.079	.244	16
	4+ Months	-.017	.080	6

	0-1 Months	.427	.670	3
Triceps Long in Rep 3 in Pronation	Healthy	-.081	.245	16
	4+ Months	-.013	.075	6
	0-1 Months	.413	.647	3
Triceps Long in Rep 3 in Supination	Healthy	.044	.032	16
	4+ Months	.072	.033	6
	0-1 Months	.197	.263	3

Table 4.32. Pairwise comparison of TB in WFE motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	**Mean**	**Std. Deviation**	**N**
Triceps Long in Rep 1 in Wrist Flexion	Healthy	.006	.168	13
	4+ Months	-.039	.084	6
	0-1 Months	.598	1.065	3
Triceps Long in Rep 1 in Wrist Extension	Healthy	.009	.165	13
	4+ Months	-.034	.085	6
	0-1 Months	.751	.950	3
Triceps Long in Rep 2 in Wrist Flexion	Healthy	.010	.166	13
	4+ Months	-.044	.080	6
	0-1 Months	.761	.943	3
Triceps Long in Rep 2 in Wrist Extension	Healthy	.010	.174	13
	4+ Months	-.050	.076	6
	0-1 Months	.754	.938	3
Triceps Long in Rep 3 in Wrist Flexion	Healthy	.008	.167	13
	4+ Months	-.048	.078	6
	0-1 Months	.781	.942	3
Triceps Long in Rep 3 in Wrist Extension	Healthy	.094	.062	13
	4+ Months	.080	.042	6
	0-1 Months	.611	.579	3

Table 4.33. Pairwise comparison of TB2 in WFE motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Wrist Flexion	Healthy	-.013	.038	13
	4+ Months	-.058	.157	6
	0-1 Months	-3.427	6.099	3
Triceps Lateral in Rep 1 in Wrist Extension	Healthy	-.010	.036	13
	4+ Months	-.065	.165	6
	0-1 Months	-3.278	5.854	3
Triceps Lateral in Rep 2 in Wrist Flexion	Healthy	-.012	.038	13
	4+ Months	-.060	.160	6
	0-1 Months	-3.468	6.170	3
Triceps Lateral in Rep 2 in Wrist Extension	Healthy	-.012	.036	13
	4+ Months	-.069	.175	6
	0-1 Months	-3.495	6.212	3
Triceps Lateral in Rep 3 in Wrist Flexion	Healthy	-.007	.037	13
	4+ Months	-.073	.164	6
	0-1 Months	-3.559	6.341	3
Triceps Lateral in Rep 3 in Wrist Extension	Healthy	-.010	.035	13
	4+ Months	-.072	.171	6
	0-1 Months	-3.528	6.213	3

Table 4.34. Pairwise comparison of TB in URD motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Ulnar Deviation	Healthy	-.013	.114	13
	4+ Months	-.050	.093	5
	0-1 Months	-5.440	9.618	4
Triceps Long in Rep 1 in Radial Deviation	Healthy	-.012	.108	13
	4+ Months	-.050	.085	5
	0-1 Months	-4.703	8.134	4
Triceps Long in Rep 2 in Ulnar Deviation	Healthy	-.013	.105	13
	4+ Months	-.048	.091	5
	0-1 Months	-5.515	9.755	4
Triceps Long in Rep 2 in Radial Deviation	Healthy	-.015	.106	13
	4+ Months	-.052	.087	5

	0-1 Months	-5.180	9.095	4
Triceps Long in Rep 3 in Ulnar Deviation	Healthy	-.015	.106	13
	4+ Months	-.040	.094	5
	0-1 Months	-5.430	9.580	4
Triceps Long in Rep 3 in Radial Deviation	Healthy	.049	.038	13
	4+ Months	.058	.037	5
	0-1 Months	.735	.946	4

Table 4.35. Pairwise comparison of ECU in URD motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	**Mean**	**Std. Deviation**	**N**
Extensor Carpi Ulnaris in Rep 1 in Ulnar Deviation	Healthy	-.005	.008	13
	4+ Months	-.024	.152	5
	0-1 Months	.683	1.305	4
Extensor Carpi Ulnaris in Rep 1 in Radial Deviation	Healthy	-.005	.008	13
	4+ Months	-.022	.155	5
	0-1 Months	.685	1.310	4
	4+ Months	-.026	.152	5
	0-1 Months	.678	1.289	4
Extensor Carpi Ulnaris in Rep 2 in Radial Deviation	Healthy	-.005	.008	13
	4+ Months	-.024	.155	5
	0-1 Months	.683	1.292	4
Extensor Carpi Ulnaris in Rep 3 in Ulnar Deviation	Healthy	-.005	.008	13
	4+ Months	-.022	.158	5
	0-1 Months	.688	1.302	4
Extensor Carpi Ulnaris in Rep 3 in Radial Deviation	Healthy	-.005	.008	13
	4+ Months	-.022	.158	5
	0-1 Months	.690	1.307	4

Table 4.36. Pairwise comparison of TB in HOC motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Hand Open	Healthy	.028	.146	12
	4+ Months	-.040	.132	7
	0-1 Months	2.653	3.087	3
Triceps Long in Rep 1 in Hand Close	Healthy	.032	.149	12
	4+ Months	-.037	.120	7
	0-1 Months	2.690	3.158	3
Triceps Long in Rep 2 in Hand Open	Healthy	.029	.146	12
	4+ Months	-.036	.130	7
	0-1 Months	2.687	3.152	3
Triceps Long in Rep 2 in Hand Close	Healthy	.032	.148	12
	4+ Months	-.039	.133	7
	0-1 Months	2.287	2.470	3
Triceps Long in Rep 3 in Hand Open	Healthy	.033	.150	12
	4+ Months	-.039	.128	7
	0-1 Months	2.703	3.188	3
Triceps Long in Rep 3 in Hand Close	Healthy	.049	.030	12
	4+ Months	.049	.033	7
	0-1 Months	.850	1.009	3

Table 4.37. Pairwise comparison of TB2 in HOC motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Hand Open	Healthy	.017	.100	12
	4+ Months	.016	.071	7
	0-1 Months	-2.837	4.862	3
Triceps Lateral in Rep 1 in Hand Close	Healthy	.018	.098	12
	4+ Months	.016	.071	7
	0-1 Months	-2.833	4.856	3
Triceps Lateral in Rep 2 in Hand Open	Healthy	.018	.099	12
	4+ Months	.017	.069	7
	0-1 Months	-2.850	4.876	3
Triceps Lateral in Rep 2 in Hand Close	Healthy	.018	.102	12
	4+ Months	.017	.069	7

	0-1 Months	-2.840	4.859	3
Triceps Lateral in Rep 3 in Hand Open	Healthy	.018	.098	12
	4+ Months	.016	.068	7
	0-1 Months	-2.870	4.928	3
Triceps Lateral in Rep 3 in Hand Close	Healthy	.019	.108	12
	4+ Months	.016	.068	7
	0-1 Months	-2.853	4.891	3

Table 4.38. Pairwise comparison of TB2 in Ball Press motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	**Mean**	**Std. Deviation**	**N**
Triceps Lateral in Rep 1 in Ball Press	Healthy	-.011	.056	14
	4+ Months	-.027	.105	3
	0-1 Months	1.524	4.051	7
	Total	.359	1.991	29
Triceps Lateral in Rep 1 in Ball Relax	Healthy	-.015	.060	14
	4+ Months	.023	.051	3
	0-1 Months	1.544	4.073	7
Triceps Lateral in Rep 2 in Ball Press	Healthy	-.011	.058	14
	4+ Months	.020	.044	3
	0-1 Months	1.526	4.054	7
Triceps Lateral in Rep 2 in Ball Relax	Healthy	-.014	.060	14
	4+ Months	.020	.036	3
	0-1 Months	1.546	4.076	7
Triceps Lateral in Rep 3 in Ball Press	Healthy	-.014	.066	14
	4+ Months	.030	.026	3
	0-1 Months	1.541	4.087	7
Triceps Lateral in Rep 3 in Ball Relax	Healthy	-.016	.062	14
	4+ Months	.017	.046	3
	0-1 Months	1.531	4.030	7

Table 4.39. Pairwise comparison of PT in Ball Press motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 in Ball Press	Healthy	-.004	.011	14
	4+ Months	.063	.101	3
	0-1 Months	-.007	.024	7
	Total	.004	.038	29
Pronator Teres in Rep 1 in Ball Relax	Healthy	-.008	.011	14
	4+ Months	.060	.095	3
	0-1 Months	-.010	.022	7
Pronator Teres in Rep 2 in Ball Press	Healthy	-.005	.012	14
	4+ Months	.057	.098	3
	0-1 Months	-.007	.024	7
Pronator Teres in Rep 2 in Ball Relax	Healthy	-.006	.009	14
	4+ Months	.060	.095	3
	0-1 Months	-.010	.022	7
Pronator Teres in Rep 3 in Ball Press	Healthy	-.005	.012	14
	4+ Months	.057	.098	3
	0-1 Months	-.006	.025	7
Pronator Teres in Rep 3 in Ball Relax	Healthy	-.006	.012	14
	4+ Months	.060	.095	3
	0-1 Months	-.011	.022	7

Table 4.40. Pairwise comparison of FCU in Ball Press motion between patients at 0–1 months of injury and 4+ months of injury using ARV

	Health	Mean	Std. Deviation	N
Flexor Carpi Ulnaris in Rep 1 in Ball Press	Healthy	-.001	.012	14
	4+ Months	.000	.000	3
	0-1 Months	-.094	.138	7
Flexor Carpi Ulnaris in Rep 1 in Ball Relax	Healthy	.001	.012	14
	4+ Months	.000	.000	3
	0-1 Months	-.083	.142	7
Flexor Carpi Ulnaris in Rep 2 in Ball Press	Healthy	.000	.013	14
	4+ Months	.003	.006	3
	0-1 Months	-.094	.142	7
Flexor Carpi Ulnaris in Rep 2 in Ball Relax	Healthy	.001	.012	14

	4+ Months	.000	.000	3
	0-1 Months	-.086	.149	7
Flexor Carpi Ulnaris in Rep 3 in Ball Press	Healthy	-.001	.011	14
	4+ Months	.003	.006	3
	0-1 Months	-.097	.146	7
Flexor Carpi Ulnaris in Rep 3 in Ball Relax	Healthy	.001	.012	14
	4+ Months	.003	.006	3
	0-1 Months	-.087	.149	7

Identical to RMS, the long and lateral heads of the triceps had a higher mean in the EFE movement in patients at their first month of therapy compared to patients in their 4th month (see Graphs A and B in Figure 4.15): long head 0–1 month mean of 0.72 ± 1.07 vs. -0.017 ± 0.08, p = 0.001 and the lateral head 0–1 month mean of -3.42 ± 6.08 vs. -0.255 ± 0.43, p = 0.016. This shows that healthier individuals use gravity to achieve elbow extension while patients opt to actively contract their triceps at a great extent to obtain the movement required. Additionally, the ECU showed significant differences with a healthy mean of -0.004 ± 0.02 vs. 0.03 ± -0.009, p = 0.017 (see Graph C in Figure 4.16). This goes with the notion that ECU's position suggests it may play a role in elbow motion however it is an inefficient way of moving it due to the almost non-existent torque production in the muscle with this motion. However, with injury, patients are more likely to recruit improper muscles to achieve the motion required. Similar to RMS, in PS, the long head of the triceps displayed greater stimulation levels in the 1-month rehabilitation population 0.39 ± 0.67 vs. -0.001 ± 0.07, p = 0.029 (Graph D in Figure 4.16). As mentioned earlier, the long head is responsible for extending the elbow and adducting the shoulder. The injury may have caused the patients to actively stimulate the triceps in order to keep the arm secured at a 90-degree angle when they were performing the wrist motions or due to keeping their arm adducted to their side. In a similar manner to PS motion in this metric and other motions in the RMS metric, the WFE motion in ARV also portrayed difference between the groups in TB and TB2 0.71 ± 1.06 vs. -0.02 ± 0.08, p = 0.001 and 3.45 ± 6.1 vs. -0.067 ± 0.16, p = 0.012 (Graph E and F in Figure 4.17). Again, this could be related to stabilizing the elbow at 90 degrees and keeping the arm close to the body.

Exactly like RMS, the URD movement, showed similar mean differences in TB 2.31 ± 9.6 vs. 0.02 ± 0.09, p = 0.3 (Graph G in Figure 4.18). In addition, the ECU depicted statistical significant differences showing patients 0–1 month at average of .68 ± 1.3 vs. 0.02 ± 1.5, p = 0.036 (Graph H in Figure 4.18). The ECU is used as a primary muscle in the URD, however, following the same conclusions previously mentioned, patients at the beginning of their therapy seem to exert more effort in recruitment to obtain the same movement as a healed or healthy individual. Analogous results are shown in the HOC with differences in TB and TB2: 2.31 ± 3.1 vs. -0.024 ± 0.13, p = 0.001 and 1.54 ± 4.86 vs. 0.014 ± 0.07, p = 0.014 (Graphs I and J in Figure 4.19). In the ball pressing motion, 3 muscles also showed significant differences. The first 2 muscles are identical to the muscles from the RMS metric and thus will not be further explained here (Graphs K and L in Figure 4.20). The muscle that showed statistical differences not presented in RMS was PT, 0.0086 ± 0.05 vs. 0.059 ± 0.10, p = 0.002 (Graph M in Figure 4.21). In a similar manner to ECU, the PT also shows anatomical relevance to moving the elbow, which allows it to agree with the notion of neuromuscular, comprise and ineffective activation of muscles.

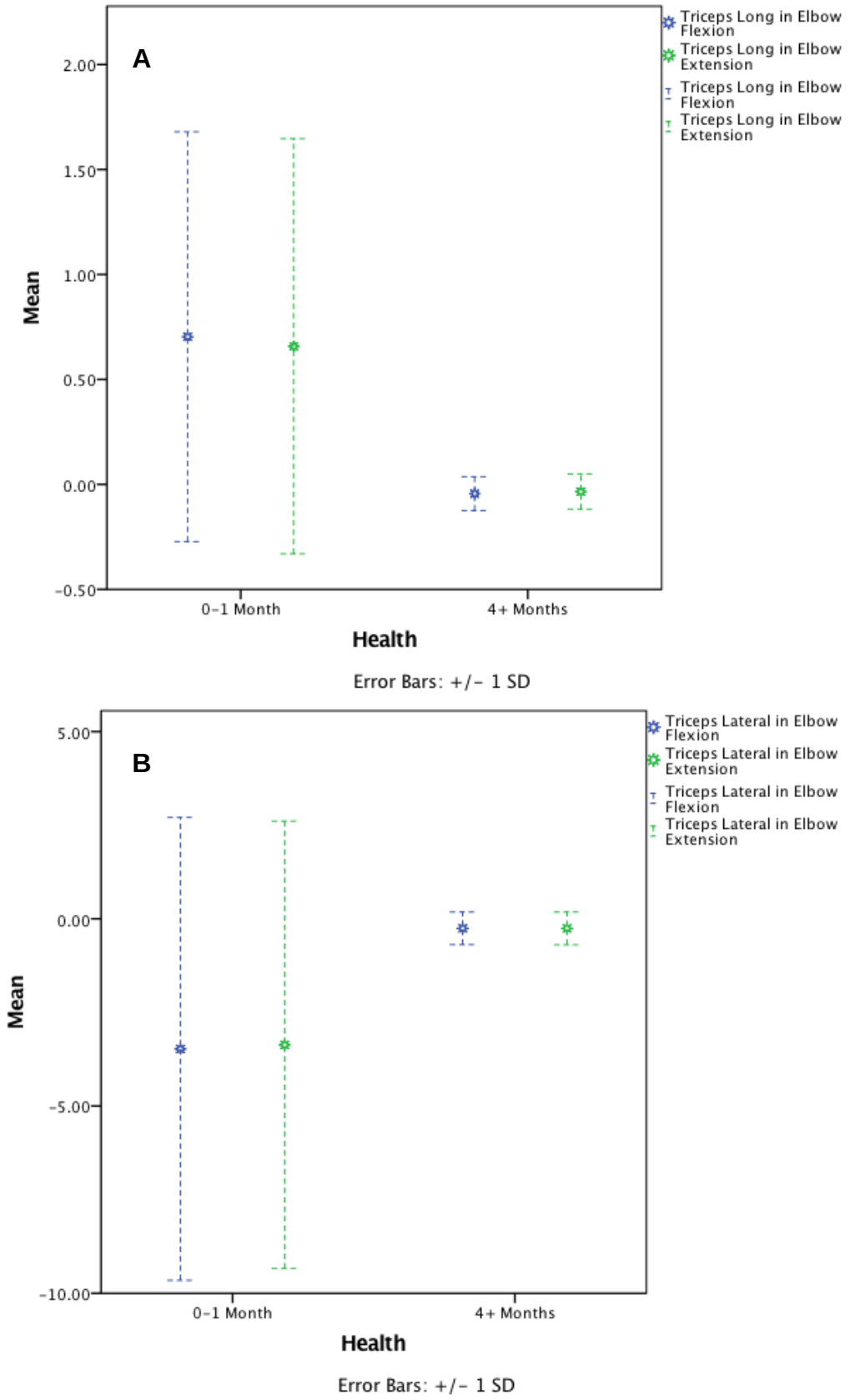


Figure 4.15. ARV means of TB in EFE (A) and TB2 in EFE (B) in early patient group and late patient group with a standard deviation +/- 1

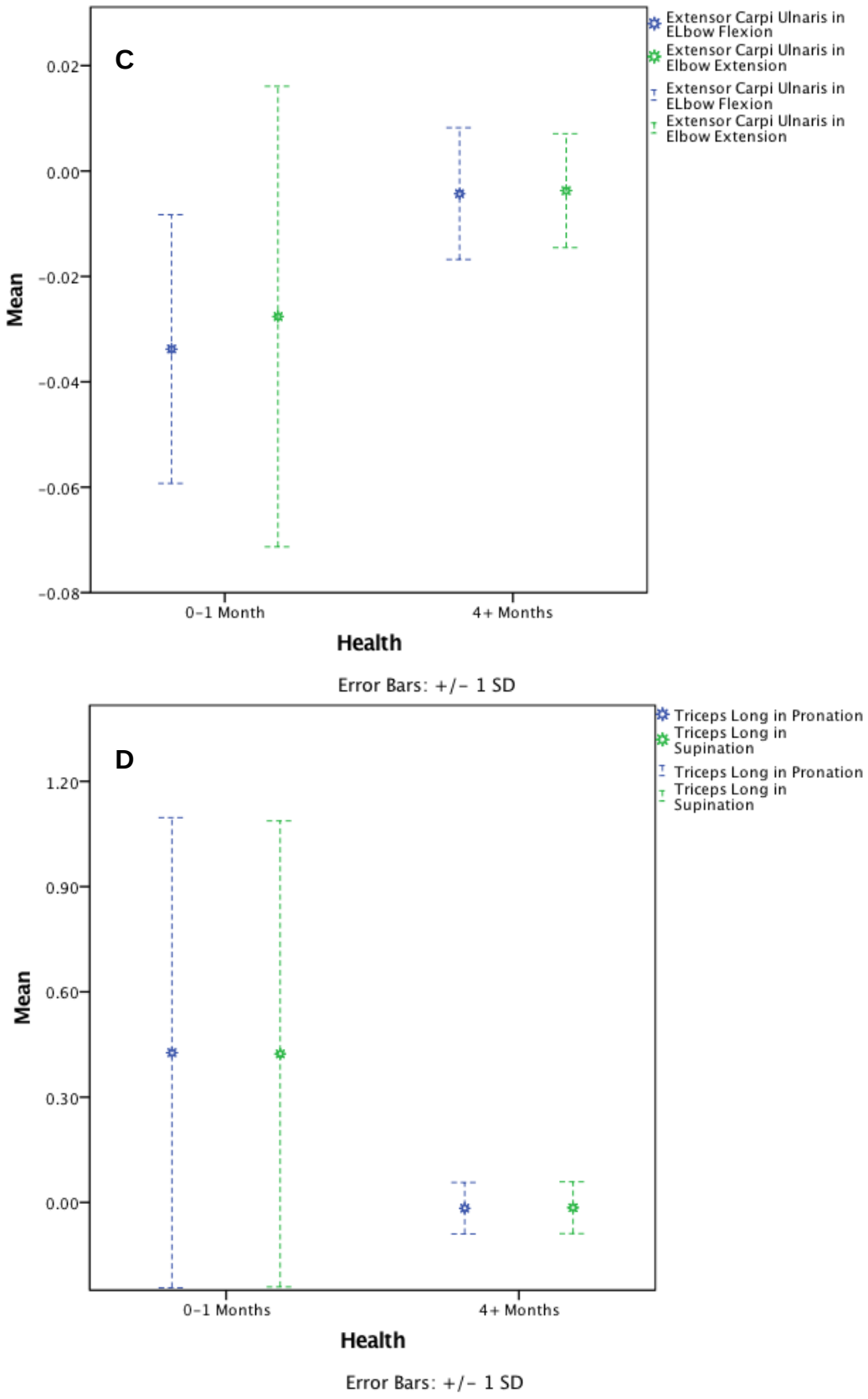


Figure 4.16. ARV means of ECU in EFE (C) and TB in PS (D) in early patient group and late patient group with a standard deviation +/- 1

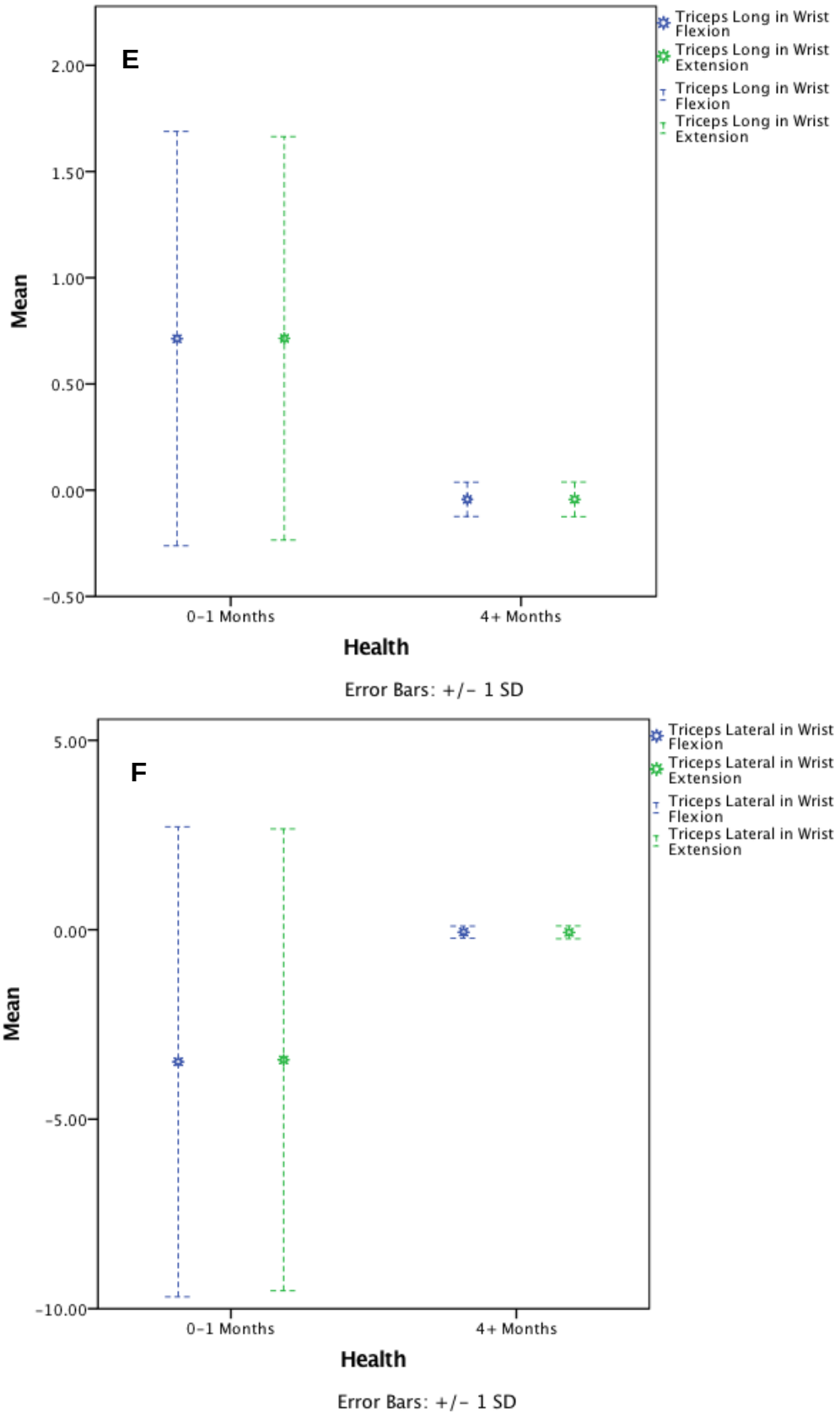


Figure 4.17. ARV means of TB in WFE (E) and TB2 in WFE (F) in early patient group and late patient group with a standard deviation +/- 1

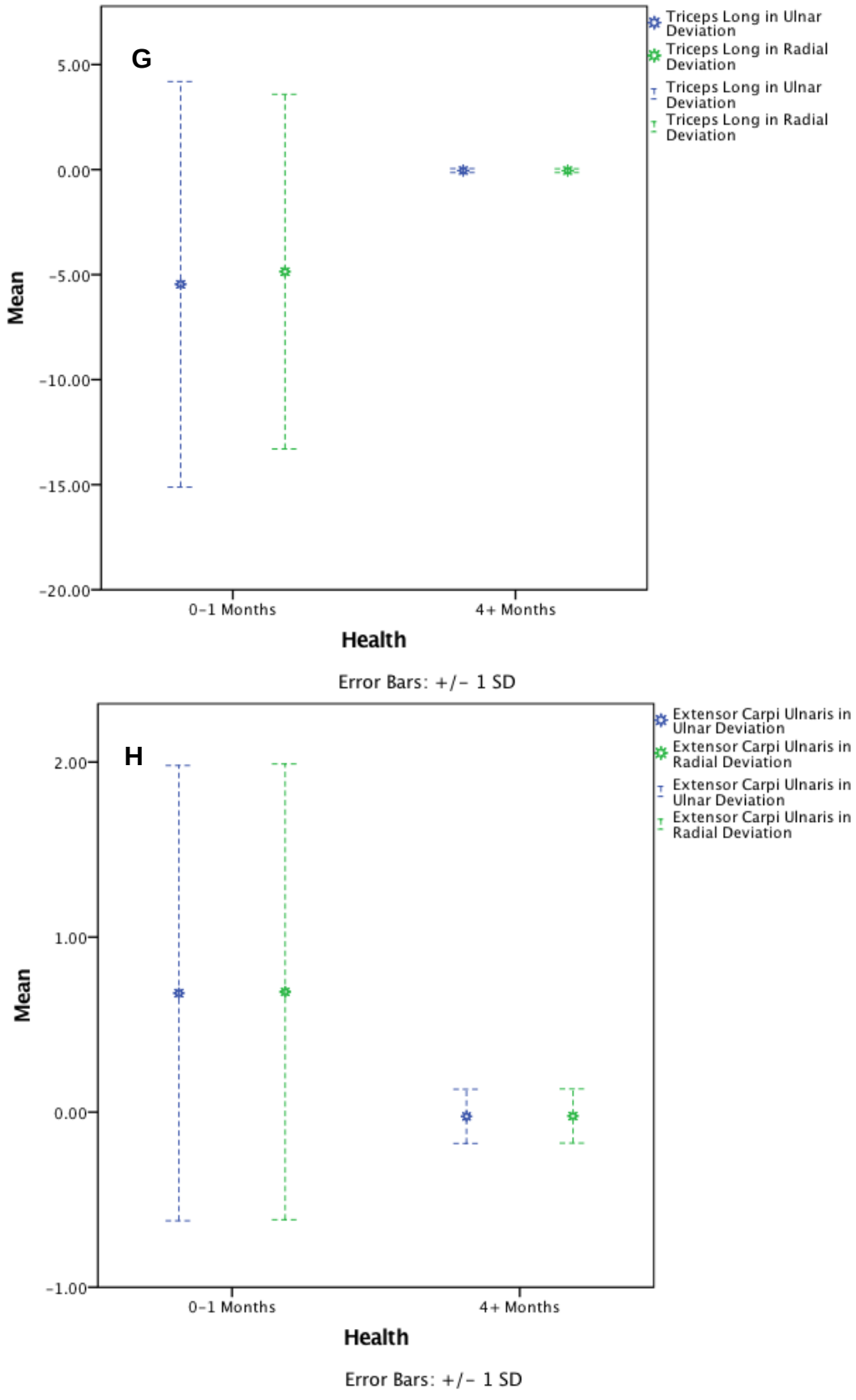


Figure 4.18. ARV means of TB in URD (G) and ECU in URD (H) motions in healthy individuals and patients with a standard deviation +/- 1

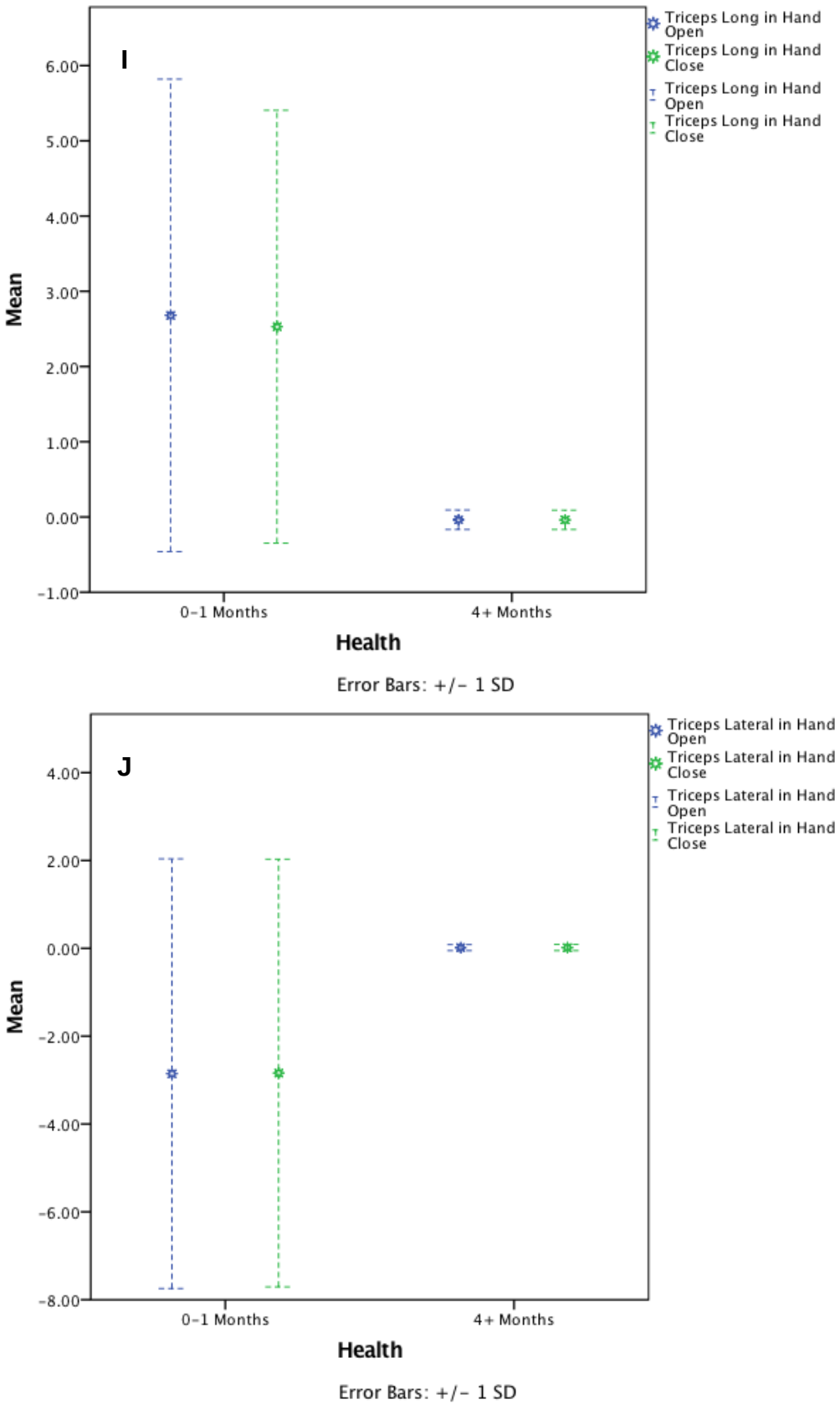


Figure 4.19. ARV means of TB in HOC (I) and TB2 in HOC (J) motions in healthy individuals and patients with a standard deviation +/- 1

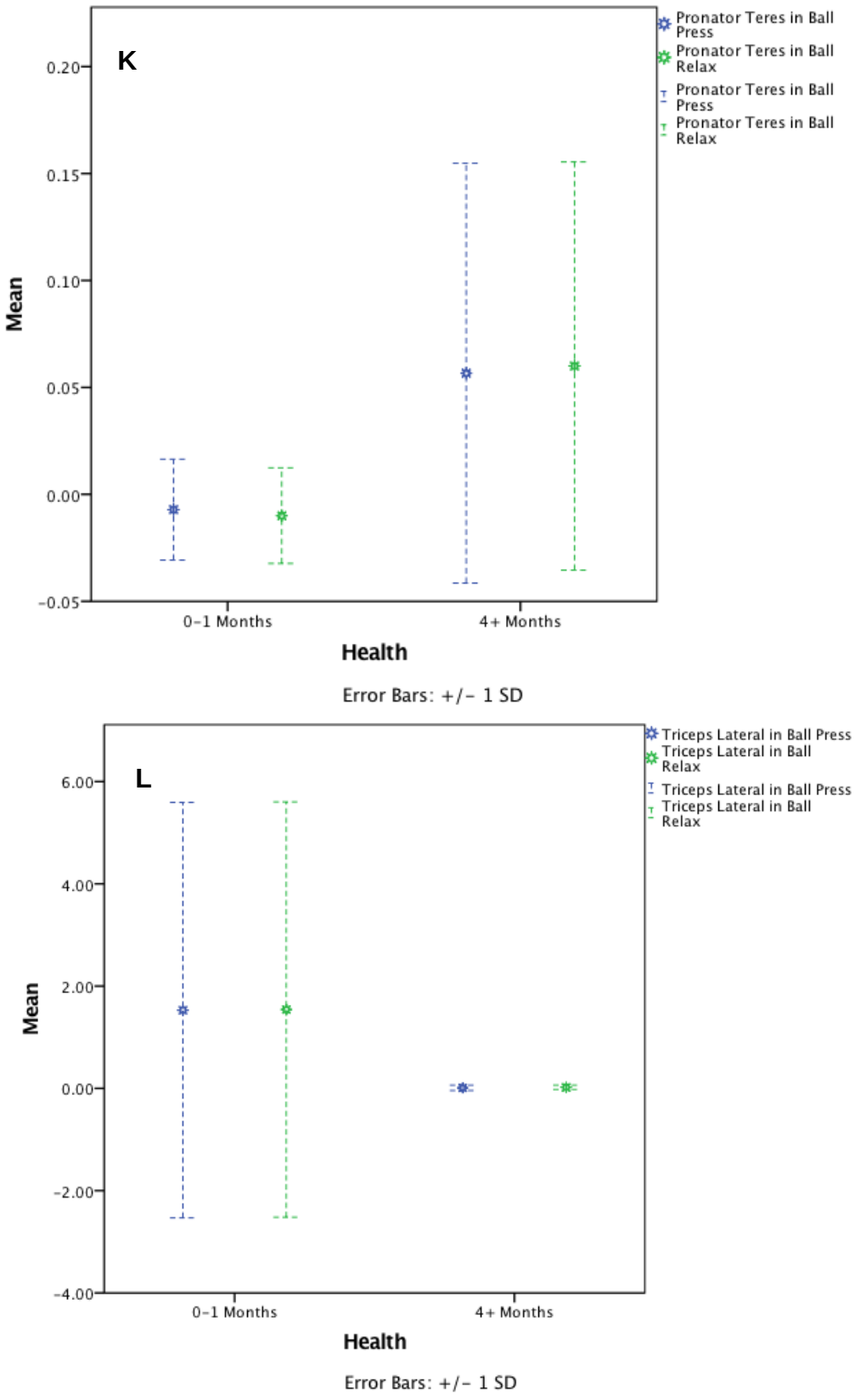


Figure 4.20. ARV means of TB2 in Ball Press (K) and FCU in Ball Press (L) motions in healthy individuals and patients with a standard deviation +/- 1

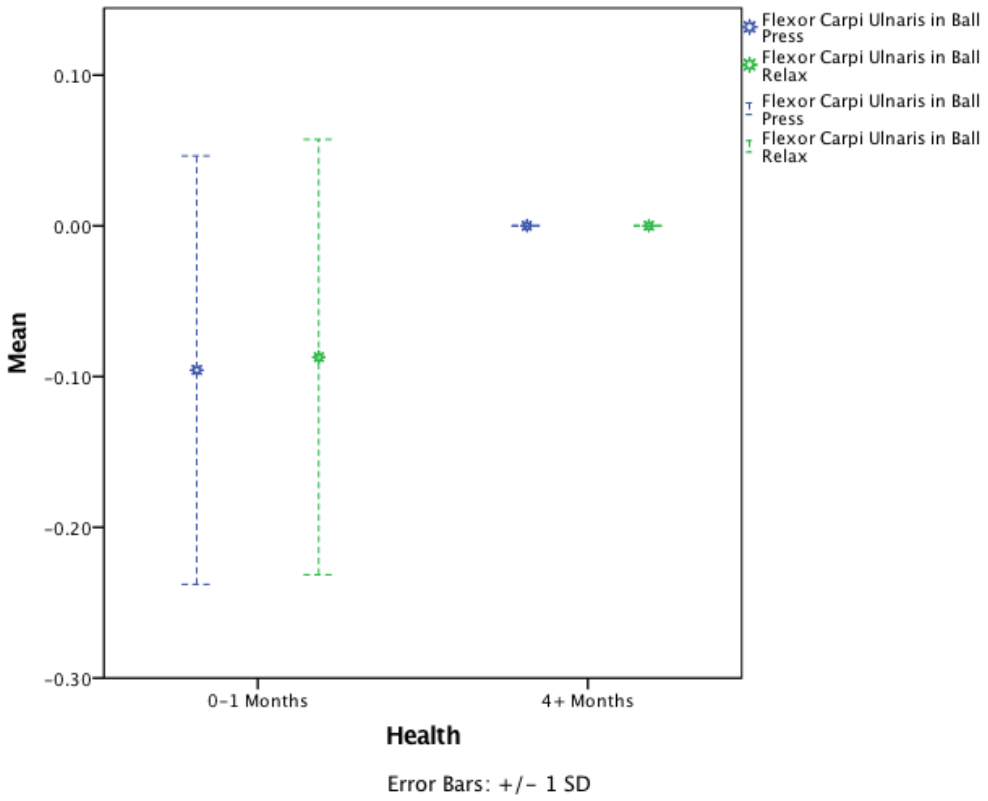


Figure 4.21. ARV means of FCU in Ball Press (M) motion in healthy individuals and patients with a standard deviation +/- 1

4.3 Zero Crossings

The ZC metric measures the number of times the raw signal crosses the zero line, i.e., the *x*-axis. This represents the level of activation, the larger the number the higher the activation in the muscle. In the first phase of analysis between patients and healthy individuals, only the elbow flexion–extension motion presented statistical significance. This was shown in the biceps and extensor carpi ulnaris as shown in Table 4.42, 4.43, 4.44, and 4.45.

Table 4.41. Statistical analysis comparing healthy individuals to patients using ZC

Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
EFE	BB	278	616	72.013	60.503	0.005	9.177
EFE	PT	271	849	189.862	159.516	0.028	5.428
EFE	ECU	303	895	167.503	140.731	0.012	7.318

Table 4.42. Statistical analysis of BB in EFE motion within each repetition comparing healthy individuals to patients using ZC

	Health	Mean	Std. Deviation	N
Biceps in Rep 1 in Elbow Flexion	Healthy	277.917	92.600	12
	Patient	616.353	397.330	17
	Total	476.310	349.795	29
Biceps in Rep 1 in Elbow Extension	Healthy	269.833	119.741	12
	Patient	488.118	365.630	17
	Total	397.793	306.586	29
Biceps in Rep 2 in Elbow Flexion	Healthy	236.417	73.190	12
	Patient	625.059	388.424	17
	Total	464.241	355.337	29
Biceps in Rep 2 in Elbow Extension	Healthy	210.833	84.992	12
	Patient	411.294	292.157	17
	Total	328.345	248.411	29
Biceps in Rep 3 in Elbow Flexion	Healthy	246.000	86.749	12
	Patient	563.118	348.053	17
	Total	431.897	312.161	29
Biceps in Rep 3 in Elbow Extension	Healthy	222.667	111.753	12
	Patient	469.294	278.350	17
	Total	367.241	253.892	29

Table 4.43. Statistical analysis of PT in EFE motion within each repetition comparing healthy individuals to patients using ZC

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 in Elbow Flexion	Healthy	459.333	570.643	12
	Patient	1031.588	1103.285	17
	Total	794.793	951.716	29
Pronator Teres in Rep 1 in Elbow Extension	Healthy	347.833	262.330	12
	Patient	738.235	858.322	17
	Total	576.690	697.357	29
Pronator Teres in Rep 2 in Elbow Flexion	Healthy	216.583	164.907	12
	Patient	1074.824	1112.491	17
	Total	719.690	950.240	29
Pronator Teres in Rep 2 in Elbow Extension	Healthy	196.917	164.934	12
	Patient	650.471	742.581	17
	Total	462.793	614.385	29
Pronator Teres in Rep 3 in Elbow Flexion	Healthy	190.417	150.425	12
	Patient	860.647	671.848	17
	Total	583.310	616.178	29
Pronator Teres in Rep 3 in Elbow Extension	Healthy	215.167	195.805	12
	Patient	736.824	718.984	17
	Total	520.966	615.485	29

Table 4.44. Statistical analysis of ECU in EFE motion within each repetition comparing healthy individuals to patients using ZC

	Health	Mean	Std. Deviation	N
Extensor Carpi Ulnaris in Rep 1 in Elbow Flexion	Healthy	393.833	343.948	12
	Patient	959.471	821.360	17
	Total	725.414	715.793	29
Extensor Carpi Ulnaris in Rep 1 in Elbow Extension	Healthy	339.250	418.067	12
	Patient	1139.647	1517.912	17
	Total	808.448	1243.469	29
Extensor Carpi Ulnaris in Rep 12 in Elbow Flexion	Healthy	306.417	241.262	12
	Patient	944.765	852.162	17
	Total	680.621	734.983	29

Extensor Carpi Ulnaris in Rep 2 in Elbow Extension	Healthy	249.500	253.235	12
	Patient	733.235	808.325	17
	Total	533.069	676.274	29
Extensor Carpi Ulnaris in Rep 3 in Elbow Flexion	Healthy	289.583	279.659	12
	Patient	904.059	631.589	17
	Total	649.793	594.584	29
Extensor Carpi Ulnaris in Rep 3 in Elbow Extension	Healthy	240.917	328.972	12
	Patient	689.294	534.634	17
	Total	503.759	506.318	29

In the biceps, the mean of healthy individuals was 277.9 ± 92.6 vs. 616.3 ± 397.3, p = 0.005, F (1,27) = 9.177 (Graph A in Figure 4.22). This is the first instance that this significance is observed in this muscle. Although an overall trend has been displayed showing higher means in patients, it was never high enough in the BB in EFE to show significance except in ZC. This metric is not amplitude dependent, as were the previous ones. As a result, more motor units could have been recruited but activated at the same level, and thus were not captured by the amplitude dependant metrics. Moreover, the pronator teres displayed a healthy mean of 271.042 ± 570.64 vs. 848.765 ± 1103.2, p = 0.028, F (1,27) = 5.42 (Graph B in Figure 4.22). Again, this has not been witnessed before in the other metrics. A similar explanation to the BB in EFE can be applied in this case. Although the PT is not a primary mover of the elbow, as mentioned before, its anatomy suggests it may play a role in the elbow joint. Lastly, the ECU showed a healthy mean of 303.25 ± 343.9 vs. 895.078 ± 821.36047, p = 0.028, F (1,27) = 5.428 (Graph C in Figure 4.23). The explanation of this is again related to the compromise of the neuromuscular function of the patient population, which leads to these muscles being activated at rate it should not be within the specified motion.

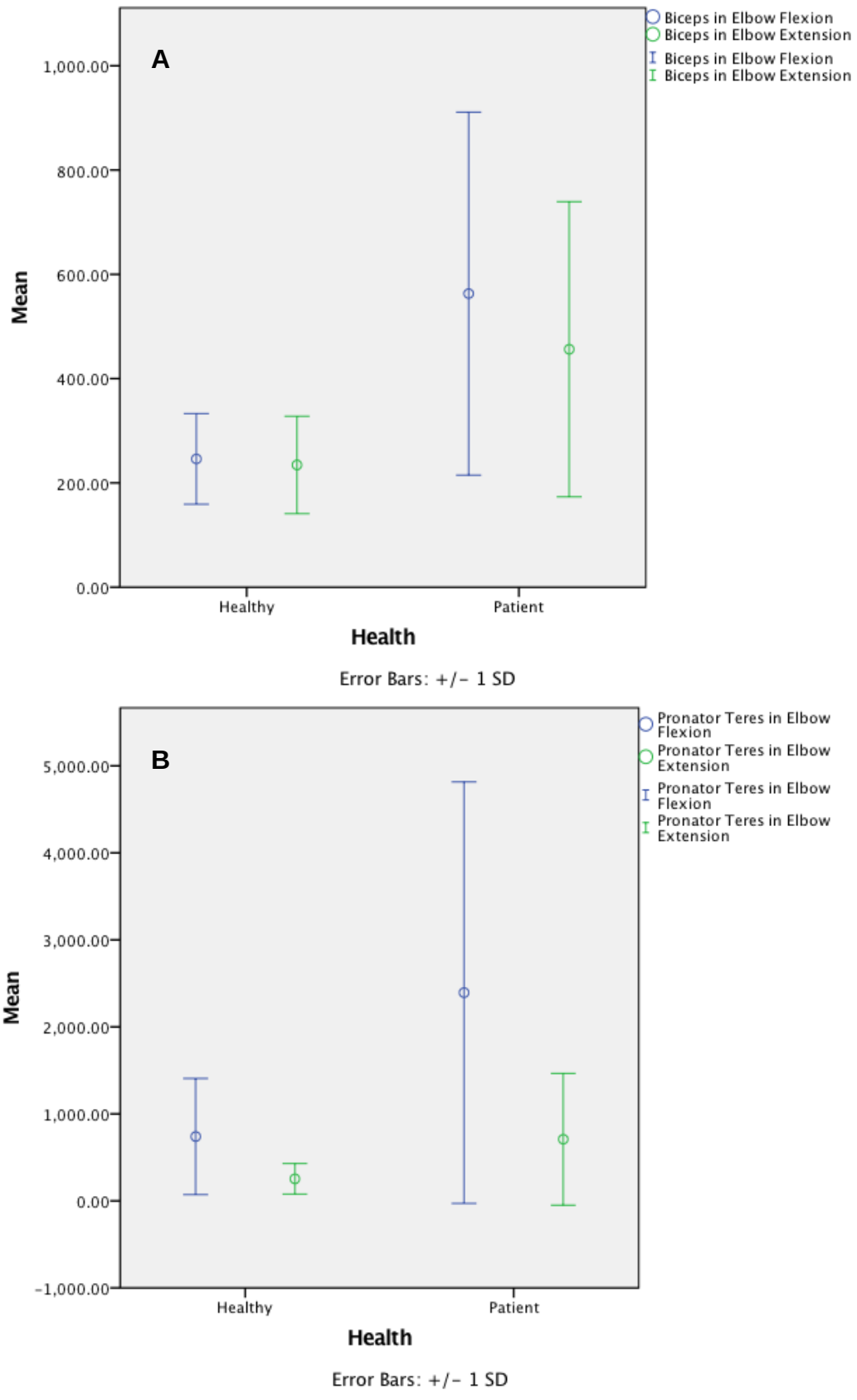


Figure 4.22. ZC Means of BB in EFE (A) and PT in EFE (B) motions in healthy individuals and patients with a standard deviation +/- 1

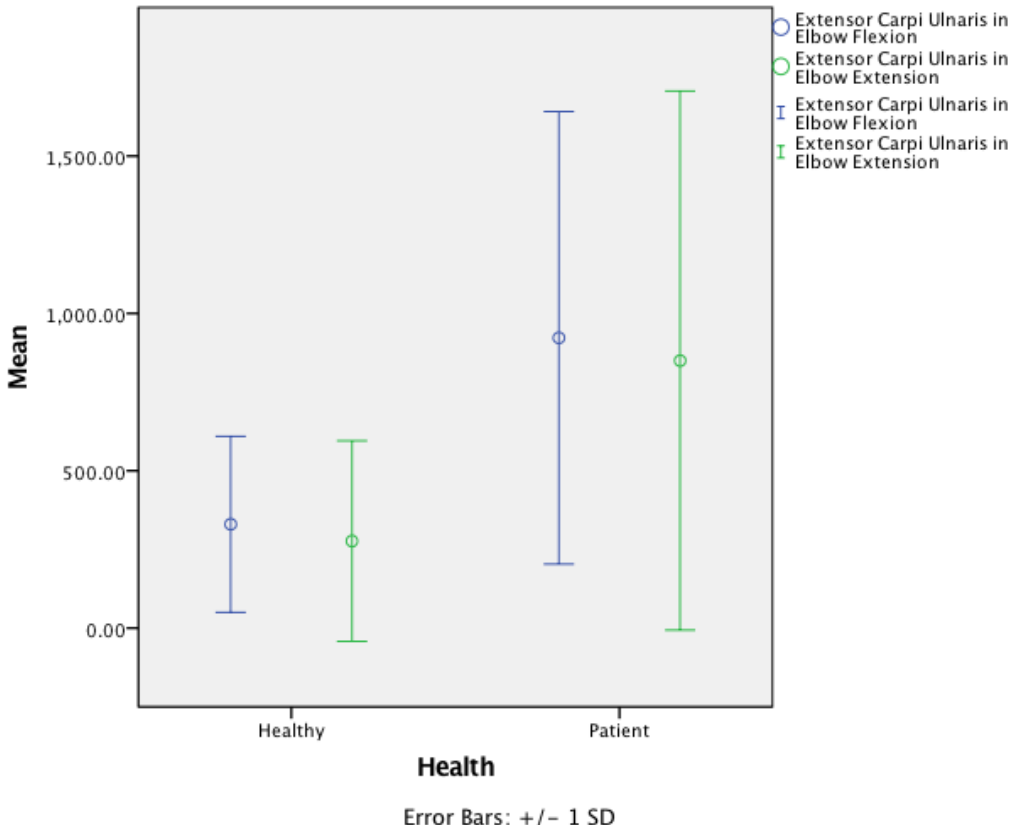


Figure 4.23. ECU in EFE (C) in healthy individuals and patients with a standard deviation +/- 1

The second part of the analysis was conducted and more instances of significances have been observed just like the previous metrics, as shown in Table 4.46, 4.47, 4.48, 4.49, 4.50, 4.51, and 4.52.

Table 4.45. Pairwise comparison between patients at 0–1 months of injury and 4+ months of injury using ZC

Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0–1 Month	SE 4+ Months	Sig
PS	TB2	864	230	220	118	0.018
PS	PT	1000	503	196	105	0.035
URD	PT	1487	374	414	271	0.035
HOC	TB2	174	703	199	130	0.038
HOC	PT	698	282	124	81	0.011
HOC	FCU	1436	475	329	215	0.024

Table 4.46. Pairwise comparison of TB2 in PS motion between patients at 0–1 months of injury and 4+ months of injury using ZC

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Pronation	Healthy	546.063	376.754	16
	4+ Months	257.571	327.094	7
	0-1 Months	801.000	335.169	2
Triceps Lateral in Rep 1 in Supination	Healthy	621.375	427.345	16
	4+ Months	252.571	343.164	7
	0-1 Months	1152.000	380.423	2
Triceps Lateral in Rep 2 in Pronation	Healthy	522.625	344.202	16
	4+ Months	290.286	349.744	7
	0-1 Months	552.500	386.787	2
Triceps Lateral in Rep 2 in Supination	Healthy	529.063	340.334	16
	4+ Months	198.857	287.086	7
	0-1 Months	968.500	422.143	2
Triceps Lateral in Rep 3 in Pronation	Healthy	486.813	337.517	16
	4+ Months	212.000	264.406	7
	0-1 Months	781.000	445.477	2
Triceps Lateral in Rep 3 in Supination	Healthy	535.313	361.933	16
	4+ Months	168.857	246.971	7
	0-1 Months	929.000	565.685	2

Table 4.47. Pairwise comparison of PT in PS motion between patients at 0–1 months of injury and 4+ months of injury using ZC

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 in Pronation	Healthy	422.625	233.896	16
	4+ Months	535.286	264.836	7
	0-1 Months	847.000	779.232	2
	Total	524.867	321.715	30
Pronator Teres in Rep 3 in Supination	Healthy	385.188	296.242	16
	4+ Months	502.286	287.191	7
	0-1 Months	1429.500	856.306	2
	Total	525.767	414.129	30
Pronator Teres in Rep 1 in Pronation	Healthy	419.438	292.712	16
	4+ Months	556.143	185.098	7
	0-1 Months	739.000	719.835	2
	Total	500.333	301.341	30
Pronator Teres in Rep 3 in Supination	Healthy	326.438	267.052	16
	4+ Months	441.714	350.676	7
	0-1 Months	1307.500	893.076	2
	Total	469.633	403.746	30
Pronator Teres in Rep 1 in Pronation	Healthy	387.438	265.395	16
	4+ Months	530.429	262.507	7
	0-1 Months	647.000	370.524	2
	Total	480.933	273.918	30
Pronator Teres in Rep 3 in Supination	Healthy	309.688	235.495	16
	4+ Months	453.857	359.589	7
	0-1 Months	1031.500	488.611	2
	Total	435.400	325.959	30

Table 4.48. Pairwise comparison of PT in URD motion between patients at 0–1 months of injury and 4+ months of injury using ZC

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 in Ulnar Deviation	Healthy	875.077	1103.841	13
	4+ Months	426.143	276.977	7
	0-1 Months	1778.333	1634.373	3
	Total	805.321	958.476	28

Pronator Teres in Rep 1 in Radial Deviation	Healthy	703.846	753.559	13
	4+ Months	342.286	222.073	7
	0-1 Months	1726.000	1408.337	3
	Total	676.893	758.666	28
Pronator Teres in Rep 2 in Ulnar Deviation	Healthy	777.538	969.752	13
	4+ Months	451.857	302.153	7
	0-1 Months	1500.667	956.202	3
	Total	729.714	777.343	28
Pronator Teres in Rep 2 in Radial Deviation	Healthy	697.308	938.688	13
	4+ Months	256.286	143.746	7
	0-1 Months	1144.000	817.669	3
	Total	590.964	721.530	28
Pronator Teres in Rep 3 in Ulnar Deviation	Healthy	814.692	784.590	13
	4+ Months	394.143	257.537	7
	0-1 Months	1434.333	825.158	3
	Total	727.714	660.304	28
Pronator Teres in Rep 3 in Radial Deviation	Healthy	687.769	740.946	13
	4+ Months	374.714	258.971	7
	0-1 Months	1341.667	996.454	3
	Total	623.536	650.816	28

Table 4.49. Pairwise comparison of TB2 in HOC motion between patients at 0–1 months of injury and 4+ months of injury using ZC

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Hand Open	Healthy	390.917	316.148	12
	4+ Months	811.714	609.895	7
	0-1 Months	171.333	139.848	3
	Total	490.960	436.556	25
Triceps Lateral in Rep 1 in Hand Close	Healthy	274.417	306.509	12
	4+ Months	617.714	470.109	7
	0-1 Months	159.333	135.633	3
	Total	366.120	359.531	25
Triceps Lateral in Rep 2 in Hand Open	Healthy	382.083	363.935	12
	4+ Months	782.714	495.615	7
	0-1 Months	175.000	144.087	3

	Total	477.960	410.263	25
Triceps Lateral in Rep 2 in Hand Close	Healthy	291.250	318.730	12
	4+ Months	665.143	502.932	7
	0-1 Months	184.333	157.912	3
	Total	403.920	380.668	25
Triceps Lateral in Rep 3 in Hand Open	Healthy	367.333	361.268	12
	4+ Months	697.857	331.890	7
	0-1 Months	177.000	116.357	3
	Total	454.640	346.226	25
Triceps Lateral in Rep 3 in Hand Close	Healthy	246.250	253.671	12
	4+ Months	644.714	483.272	7
	0-1 Months	179.667	143.959	3
	Total	383.320	358.067	25

Table 4.50. Pairwise comparison of PT in HOC motion between patients at 0–1 months of injury and 4+ months of injury using ZC

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 in Hand Open	Healthy	569.833	231.247	12
	4+ Months	329.000	275.247	7
	0-1 Months	680.000	321.053	3
Pronator Teres in Rep 1 in Hand Close	Healthy	376.833	169.938	12
	4+ Months	274.714	256.992	7
	0-1 Months	700.333	397.588	3
Pronator Teres in Rep 2 in Hand Open	Healthy	523.167	204.453	12
	4+ Months	313.429	270.955	7
	0-1 Months	689.667	333.800	3
Pronator Teres in Rep 2 in Hand Close	Healthy	370.417	182.488	12
	4+ Months	209.286	165.755	7
	0-1 Months	710.333	453.202	3
Pronator Teres in Rep 3 in Hand Open	Healthy	556.833	187.869	12
	4+ Months	329.286	314.103	7
	0-1 Months	658.667	279.502	3
Pronator Teres in Rep 3 in Hand Close	Healthy	332.000	165.723	12
	4+ Months	237.000	197.020	7
	0-1 Months	749.333	440.320	3

Table 4.51. Pairwise comparison of FCU in HOC motion between patients at 0–1 months of injury and 4+ months of injury using ZC

	Health	Mean	Std. Deviation	N
Flexor Carpi Ulnaris in Rep 1 in Hand Open	Healthy	543.917	292.813	12
	4+ Months	509.286	658.178	7
	0-1 Months	1293.333	1471.633	3
Flexor Carpi Ulnaris in Rep 1 in Hand Close	Healthy	416.083	283.765	12
	4+ Months	475.571	733.207	7
	0-1 Months	1453.333	792.249	3
Flexor Carpi Ulnaris in Rep 2 in Hand Open	Healthy	517.250	300.763	12
	4+ Months	423.714	485.144	7
	0-1 Months	1373.000	1615.878	3
Flexor Carpi Ulnaris in Rep 2 in Hand Close	Healthy	391.750	247.399	12
	4+ Months	501.714	857.034	7
	0-1 Months	1634.333	1358.693	3
Flexor Carpi Ulnaris in Rep 3 in Hand Open	Healthy	545.167	283.157	12
	4+ Months	424.143	440.560	7
	0-1 Months	1372.667	1151.289	3
Flexor Carpi Ulnaris in Rep 3 in Hand Close	Healthy	350.667	271.769	12
	4+ Months	513.286	909.423	7
	0-1 Months	1494.667	1025.132	3

In the TB2 in PS, the mean of 0–1 month individuals was 864 ± 335 vs. 230 ± 327, p = 0.018 (Graph A in Figure 4.24). The higher value in the more recently injured population aligns with the conclusions that have been drawn thus far in this thesis. Moreover, the 0–1 group also exhibited higher rate of crossings than the 4+ group in PT in PS as well 1000 ± 779 vs. 503 ± 265, p = 0.035 (Graph B in Figure 4.25). This is analogous to the previous findings as well. Additionally, the PT and FCU also showed higher values in HOC in the 0–1 month group: 698 ± 321 vs. 282 ± 275, p = 0.011 and 1436 ± 1471 vs. 475 ± 658, p = 0.024 respectively (Graphs E and F in Figures 4.26 and 4.27). Similar to the previous discussion, these muscles are not responsible for opening and closing the fingers yet show these statistical differences. In URD motion, the PT showed yet another higher mean in the early rehab patient group: 1487 ± 1634 vs. 374 ± 276, p = 0.035 (Graph C in Figure 4.25). Finally, the TB2 in HOC also shows statistical differences but with a higher mean in healthier group: 174 ± 104 vs. 703 ± 610, p = 0.038 (Graph D in Figure 4.26). This is not in accordance with previous findings. This variation may be

attributed to the use of this different metric that measures rate rather than amplitude or it could be explained by the inability of patients to contract the muscle, and therefore it does not show high levels of activation.

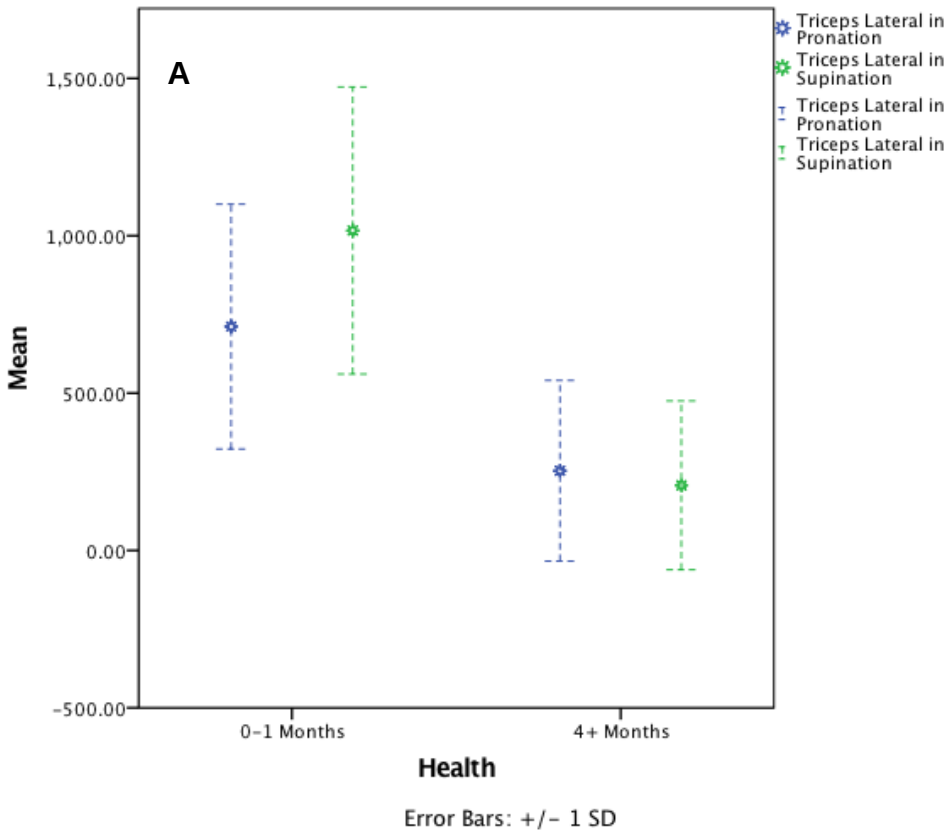


Figure 4.24. ZC measure of TB2 in PS (A) motion in early patient group and late patient group with a standard deviation +/- 1

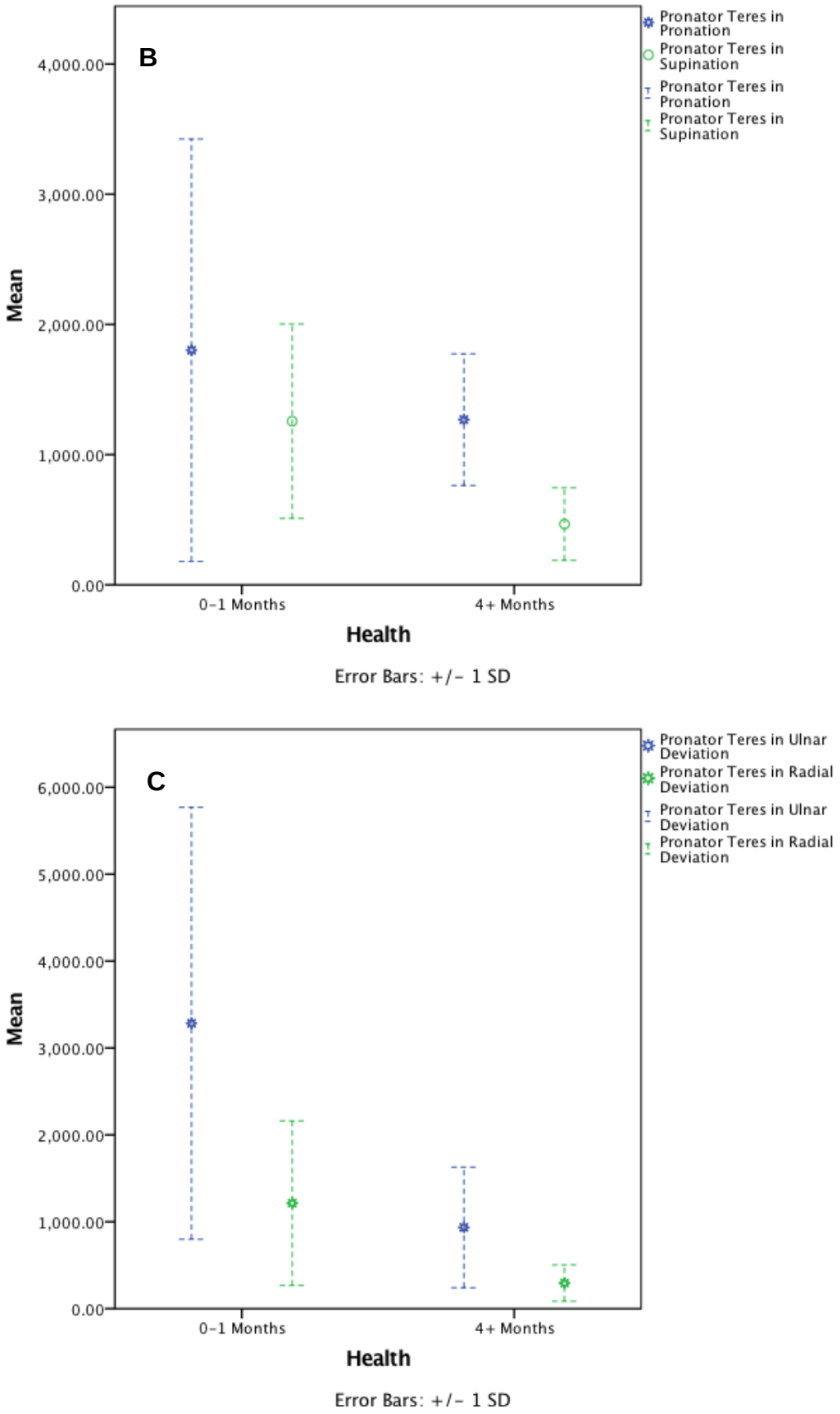


Figure 4.25. ZC measure of PT in PS (B) and PT in URD (C) motions in early patient group and late patient group with a standard deviation +/- 1

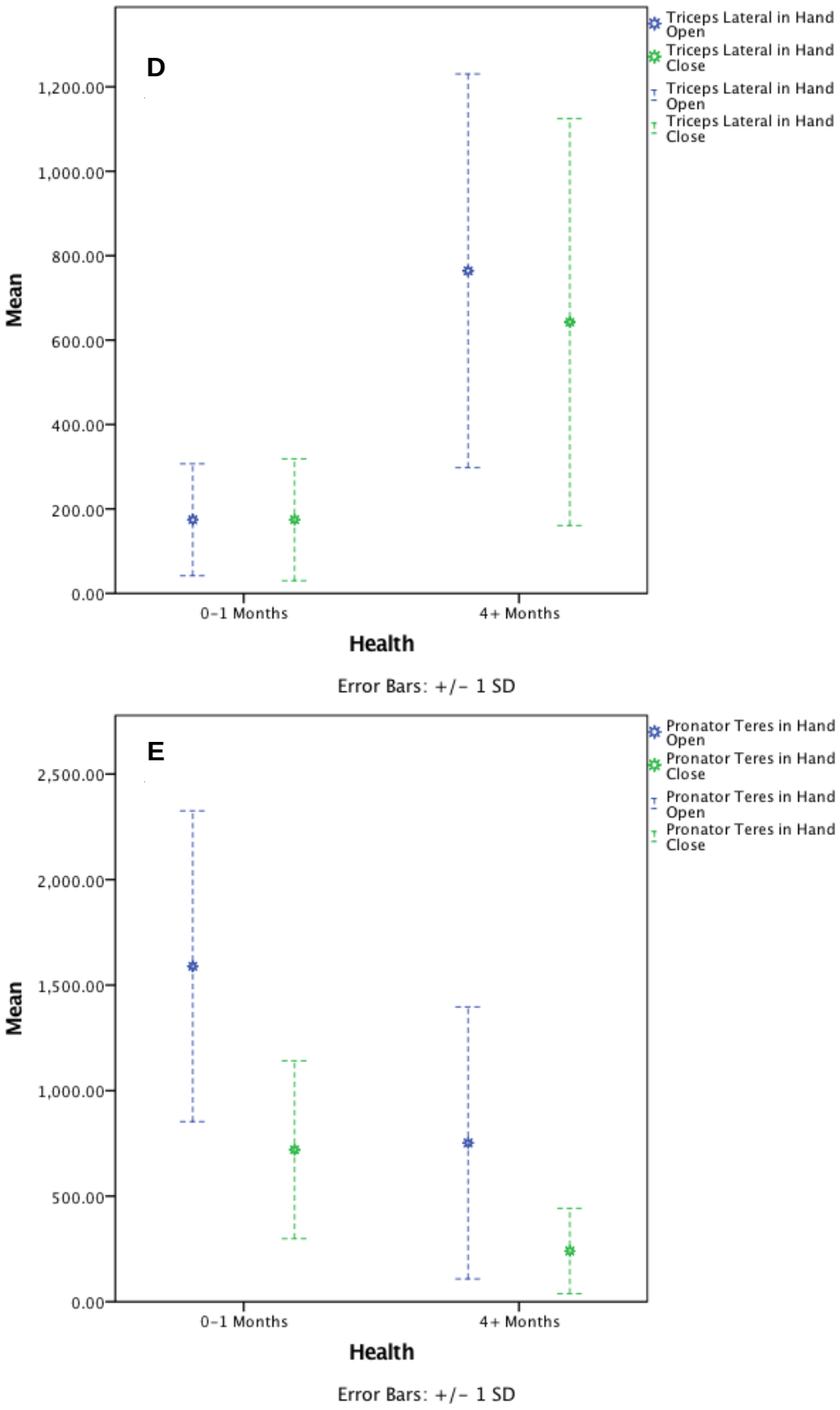


Figure 4.26. ZC measure of TB2 in HOC (B), PT in HOC (C) motions in early patient group and late patient group with a standard deviation +/- 1

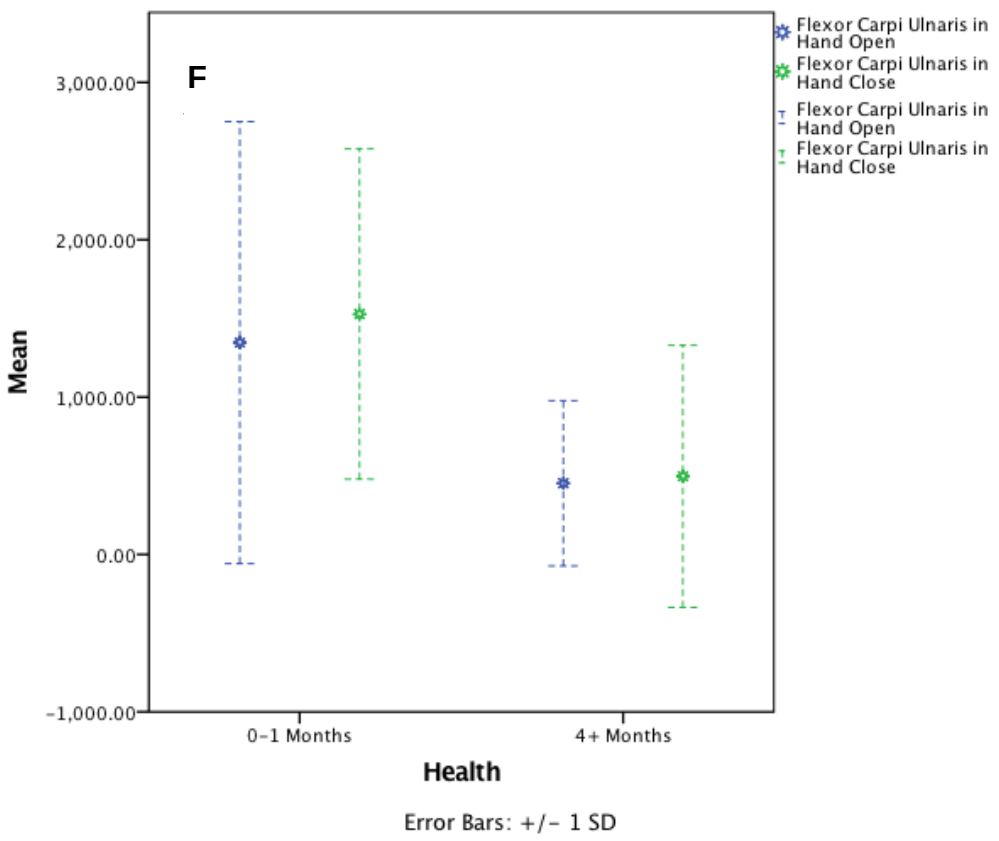


Figure 4.27. ZC measure of FCU in HOC (F) motion in early patient group and late patient group with a standard deviation +/- 1

4.4 MSA

Another metric that revealed statistical significance was the MSA. During the first analysis, three instances exhibited significance as shown in Table 4.53, 4.54, 4.55, and 4.56.

Table 4.52. Statistical analysis comparing healthy individuals to patients using MSA

Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
EFE	TB2	0.122	0.392	0.089	0.093	0.046	4.397
PS	TB	0.154	0.416	0.083	0.086	0.037	4.838
Ball	BB	0.314	0.199	0.029	0.028	0.008	8.102

Table 4.53. Statistical analysis of TB2 in EFE motion within each repetition comparing healthy individuals to patients using MSA

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Elbow Flexion	Healthy	.118	.081	14
	Patient	.358	.474	13
	Total	.234	.349	27
Triceps Lateral in Rep 1 in Elbow Extension	Healthy	.125	.089	14
	Patient	.347	.500	13
	Total	.232	.364	27
Triceps Lateral in Rep 2 in Elbow Flexion	Healthy	.124	.091	14
	Patient	.424	.489	13
	Total	.268	.371	27
Triceps Lateral in Rep 2 in Elbow Extension	Healthy	.101	.057	14
	Patient	.308	.439	13
	Total	.201	.319	27
Triceps Lateral in Rep 3 in Elbow Flexion	Healthy	.127	.116	14
	Patient	.538	.832	13
	Total	.325	.608	27
Triceps Lateral in Rep 3 in Elbow Extension	Healthy	.137	.110	14
	Patient	.378	.512	13
	Total	.253	.377	27

Table 4.54. Statistical analysis of TB in PS motion within each repetition comparing healthy individuals to patients using MSA

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Pronation	Healthy	.151	.104	14
	Patient	.412	.443	13
	Total	.276	.337	27
Triceps Long in Rep 1 in Supination	Healthy	.156	.103	14
	Patient	.392	.423	13
	Total	.270	.320	27
Triceps Long in Rep 2 in Pronation	Healthy	.149	.100	14
	Patient	.426	.429	13
	Total	.282	.332	27
Triceps Long in Rep 2 in Supination	Healthy	.158	.103	14
	Patient	.406	.431	13

	Total	.277	.327	27
Triceps Long in Rep 3 in Pronation	Healthy	.151	.100	14
	Patient	.444	.444	13
	Total	.292	.344	27
Triceps Long in Rep 3 in Supination	Healthy	.161	.115	14
	Patient	.417	.439	13
	Total	.284	.336	27

Table 4.55. Statistical analysis of BB in Ball Press motion within each repetition comparing healthy individuals to patients using MSA

	Health	Mean	Std. Deviation	N
Biceps in Rep 1 in Ball Press	Healthy	.348	.142	14
	Patient	.227	.127	15
	Total	.285	.146	29
Biceps in Rep 1 in Ball Relax	Healthy	.244	.151	14
	Patient	.154	.060	15
	Total	.198	.120	29
Biceps in Rep 2 in Ball Press	Healthy	.371	.130	14
	Patient	.237	.128	15
	Total	.301	.144	29
Biceps in Rep 2 in Ball Relax	Healthy	.234	.148	14
	Patient	.148	.046	15
	Total	.190	.115	29
Biceps in Rep 3 in Ball Press	Healthy	.454	.310	14
	Patient	.243	.146	15
	Total	.345	.258	29
Biceps in Rep 3 in Ball Relax	Healthy	.234	.122	14
	Patient	.185	.072	15
	Total	.209	.100	29

In elbow flexion–extension only the lateral head of the triceps showed statistical significance with a healthy mean of 0.122 ± 0.08 vs. 0.392 ± 0.47, p = 0.046, F (1,25) = 4.397 (Graph A in Figure 4.28). This aligns with the evaluations made in the previous metrics about using the muscle rather than gravity in patients. In pronation–supination, TB revealed a p value of significance with a healthy mean of 0.154 ± 0.1 vs. 0.416 ± 0.44, p = 0.037, F (1,28) = 4.838 (Graph B in Figure 4.29). Again, the elbow is being

held at an angle of 90 degrees therefore this muscle is being activated in this manner. Finally, the BB revealed statistical differences in ball pressing motion between healthy individuals and the patient population 0.314 ± 0.1423 vs. 0.199 ± 0.12715, $p = 0.008$, $F(1,27) = 8.102$ (Graph C in Figure 4.29). Unlike the general trend of a greater mean in patients, it is greater in healthy individuals in this instance. This is probably due to the lack in strength in the triceps of most individuals so they shifted their arm in such a way that they activated the biceps to achieve a stronger press down on the ball.

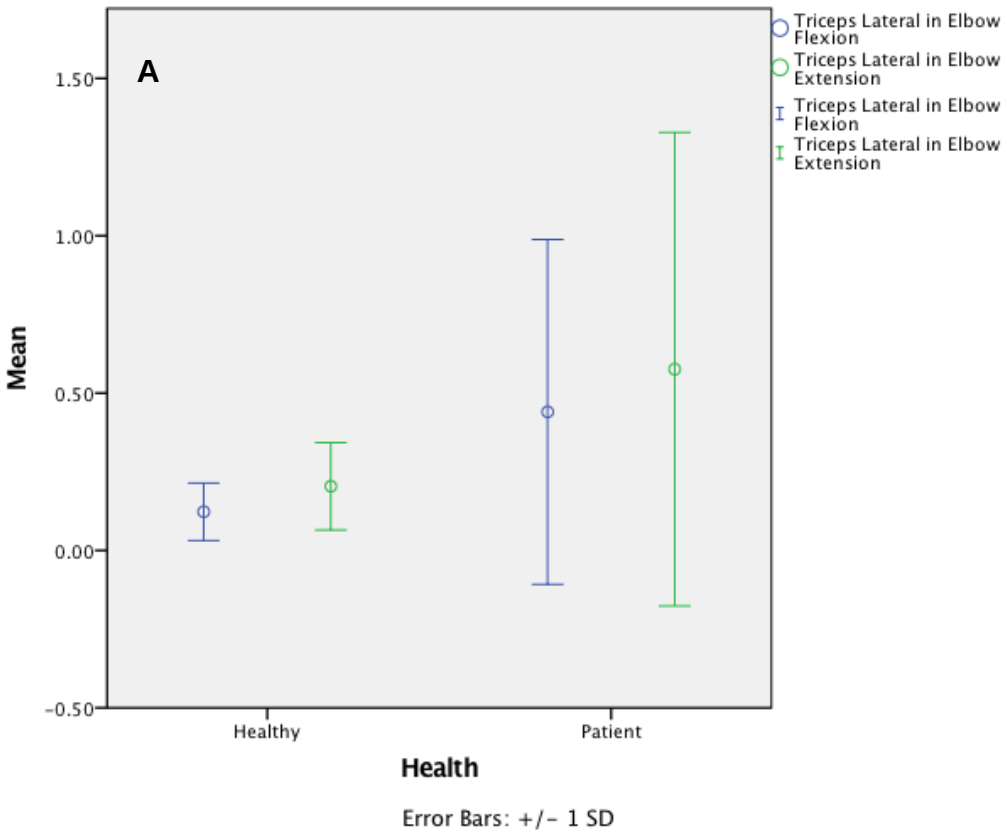
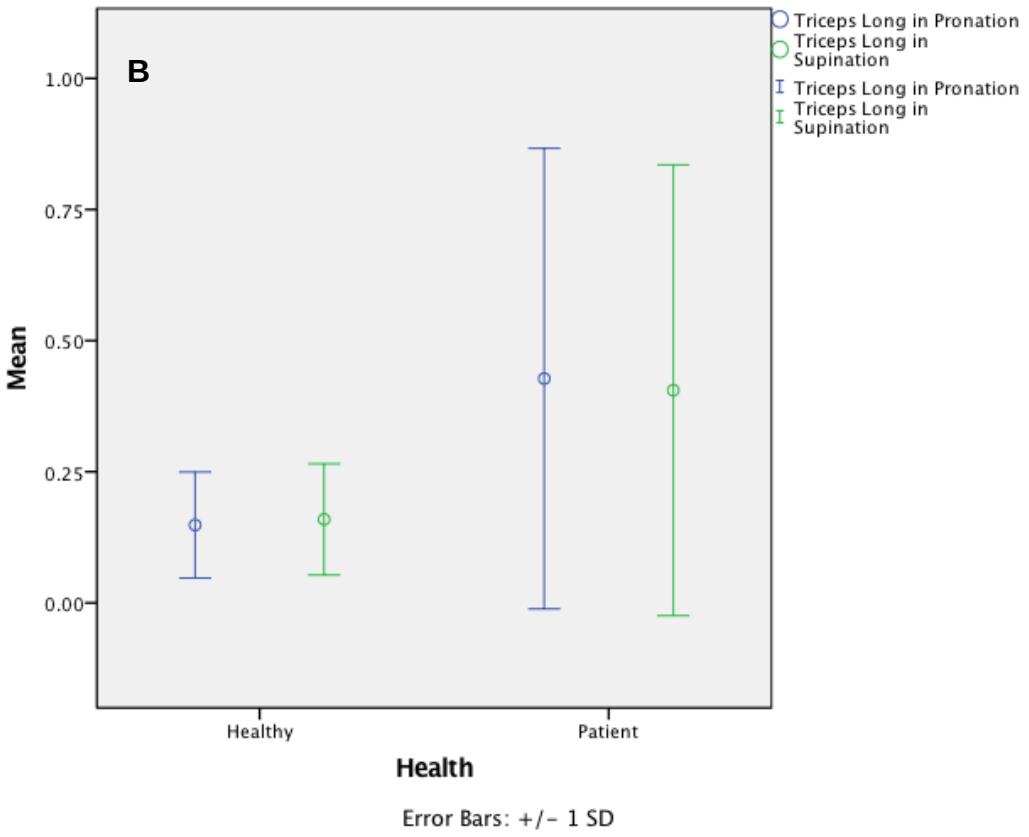


Figure 4.28. MSA measure of TB2 in EFE (A) motion in healthy individuals and patients with a standard deviation +/- 1



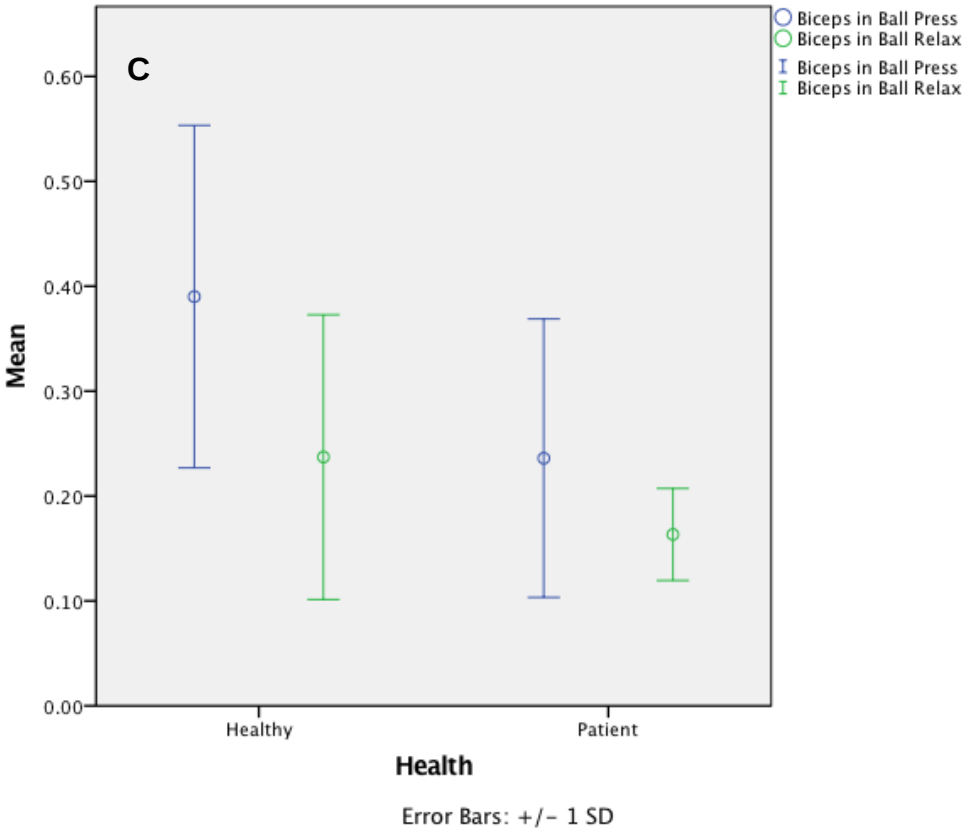


Figure 4.29. MSA measure of TB in PS (B) and BB in Ball Pressing (C) motion in healthy individuals and patients with a standard deviation +/- 1

Next, the second and final analysis done within the patient population in two groups of healing levels will be discussed. As Table 4.57, 4.58, 4.59, 4.60, 4.61, and 4.62 show, there were 5 instances of significant differences.

Table 4.56. Pairwise comparison between patients at 0–1 months of injury and 4+ months of injury using MSA

Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0–1 Month	SE 4+ Months	Sig.
EFE	TB	0.600000	-0.040000	0.176879	0.136295	0.001
EFE	TB2	-3.426667	-0.060000	0.159437	0.112739	0.012
PS	PT	0.100000	0.693333	0.162585	0.114965	0.035
URD	TB	0.750000	0.283333	0.223235	0.157851	0.004
BALL	TB2	2.660000	0.466667	0.602308	0.491782	0.019

Table 4.57. Pairwise comparison of TB in EFE motion between patients at 0–1 months of injury and 4+ months of injury using MSA

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Elbow Flexion	Healthy	.005	.167	13
	4+ Months	-.040	.086	6
	0-1 Months	.600	1.067	3
Triceps Long in Rep 1 in Elbow Extension	Healthy	.009	.165	13
	4+ Months	-.033	.088	6
	0-1 Months	.750	.949	3
Triceps Long in Rep 2 in Elbow Flexion	Healthy	.011	.167	13
	4+ Months	-.043	.078	6
	0-1 Months	.760	.943	3
Triceps Long in Rep 2 in Elbow Extension	Healthy	.009	.173	13
	4+ Months	-.048	.075	6
	0-1 Months	.753	.939	3
Triceps Long in Rep 3 in Elbow Flexion	Healthy	.008	.169	13
	4+ Months	-.047	.078	6
	0-1 Months	.783	.945	3
Triceps Long in Rep 3 in Elbow Extension	Healthy	.092	.061	13
	4+ Months	.080	.044	6
	0-1 Months	.610	.580	3

Table 4.58. Pairwise comparison of TB2 in EFE motion between patients at 0–1 months of injury and 4+ months of injury using MSA

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Elbow Flexion	Healthy	-.013	.038	13
	4+ Months	-.060	.157	6
	0-1 Months	-3.427	6.101	3
Triceps Lateral in Rep 1 in Elbow Extension	Healthy	-.009	.035	13
	4+ Months	-.063	.164	6
	0-1 Months	-3.280	5.856	3
Triceps Lateral in Rep 2 in Elbow Flexion	Healthy	-.012	.038	13
	4+ Months	-.060	.162	6
	0-1 Months	-3.467	6.170	3
Triceps Lateral in Rep 2 in Elbow Extension	Healthy	-.013	.036	13
	4+ Months	-.070	.177	6
	0-1 Months	-3.497	6.213	3
Triceps Lateral in Rep 3 in Elbow Flexion	Healthy	-.008	.036	13
	4+ Months	-.073	.164	6
	0-1 Months	-3.560	6.341	3
Triceps Lateral in Rep 3 in Elbow Extension	Healthy	-.010	.036	13
	4+ Months	-.072	.169	6
	0-1 Months	-3.530	6.210	3

Table 4.59. Pairwise comparison of TB2 in EFE motion between patients at 0–1 months of injury and 4+ months of injury using MSA

	Health	Mean	Std. Deviation	N
Pronator Teres in Rep 1 in Pronation	Healthy	.217	.134	13
	4+ Months	.693	.563	6
	0-1 Month	.100	.035	3
Pronator Teres in Rep 1 in Supination	Healthy	.118	.102	13
	4+ Months	.403	.505	6
	0-1 Month	.100	.017	3
Pronator Teres in Rep 2 in Pronation	Healthy	.218	.103	13
	4+ Months	.743	.616	6
	0-1 Month	.230	.210	3
Pronator Teres in Rep 2 in Supination	Healthy	.107	.068	13
	4+ Months	.465	.581	6

	0-1 Month	.110	.046	3
Pronator Teres in Rep 3 in Pronation	Healthy	.229	.127	13
	4+ Months	.780	.628	6
	0-1 Month	.207	.195	3
Pronator Teres in Rep 3 in Supination	Healthy	.099	.054	13
	4+ Months	.510	.655	6
	0-1 Month	.123	.047	3

Table 4.60. Pairwise comparison of TB2 in EFE motion between patients at 0–1 months of injury and 4+ months of injury using MSA

	Health	Mean	Std. Deviation	N
Triceps Long in Rep 1 in Ulnar Deviation	Healthy	.174	.106	11
	4+ Months	.283	.243	6
	0-1 Month	.750	.988	3
Triceps Long in Rep 1 in Radial Deviation	Healthy	.176	.109	11
	4+ Months	.273	.236	6
	0-1 Month	.817	1.094	3
Triceps Long in Rep 2 in Ulnar Deviation	Healthy	.193	.115	11
	4+ Months	.288	.249	6
	0-1 Month	.750	.987	3
Triceps Long in Rep 12 in Radial Deviation	Healthy	.186	.113	11
	4+ Months	.277	.235	6
	0-1 Month	.810	1.057	3
Triceps Long in Rep 3 in Ulnar Deviation	Healthy	.193	.124	11
	4+ Months	.285	.248	6
	0-1 Month	.790	1.048	3
Triceps Long in Rep 3 in Radial Deviation	Healthy	.186	.115	11
	4+ Months	.267	.218	6
	0-1 Month	.790	1.022	3

Table 4.61. Pairwise comparison of TB2 in Ball Press motion between patients at 0–1 months of injury and 4+ months of injury using MSA

	Health	Mean	Std. Deviation	N
Triceps Lateral in Rep 1 in Ball Press	Healthy	.689	.560	11
	4+ Months	.467	.359	3
	0-1 Month	2.660	2.942	2
Triceps Lateral in Rep 1 in Ball Relax	Healthy	.283	.365	11
	4+ Months	.210	.161	3
	0-1 Month	2.430	3.380	2
Triceps Lateral in Rep 2 in Ball Press	Healthy	.792	.575	11
	4+ Months	.500	.484	3
	0-1 Month	2.695	2.934	2
Triceps Lateral in Rep 2 in Ball Relax	Healthy	.138	.084	11
	4+ Months	.163	.162	3
	0-1 Month	2.460	3.408	2
Triceps Lateral in Rep 3 in Ball Press	Healthy	.793	.619	11
	4+ Months	.450	.406	3
	3-4 Months	.200	.	1
	1-2 Months	.418	.235	4
	0-1 Month	2.675	3.033	2
Triceps Lateral in Rep 3 in Ball Relax	Healthy	.176	.205	11
	4+ Months	.143	.155	3
	0-1 Month	2.340	3.267	2

The TB and TB2 muscles showed significant differences in EFE (Graph A and B in Figure 4.30) and in URD (Graph D in Figure 4.31). The TB in EFE showed a mean of 0.6 ± 1.907 vs. -0.04 ± 0.086, p = 0.037. TB2 in EFE exhibited a mean of -3.43 ± 6.1 vs. -0.06 ± 0.157, p = 0.037. Once again, the TB showed significance in URD, 0.75 ± 0.99 vs. 0.28 ± 0.24, p = 0.037, which was determined to be caused by holding the elbow at a right angle. In EFE and URD, an explanation that has been repeated through the various metrics was determined and was applied to this metric as well. Likewise, the PT being activated at a higher degree in healthier individuals than the earlier trauma patients has also been discussed and mentioned: 0.1 ± 0.035 vs. -0.06 ± 0.56, p = 0.035 (Graph C in Figure 4.31) Finally, as expected, the triceps showed a higher value in the 0–1 group versus the 4+ group, 2.66 ± 2.94 vs. 0.47 ± 0.36, p = 0.019, which aligns with the trend detected in higher values of less healthy patients (Graph E in Figure 4.32).

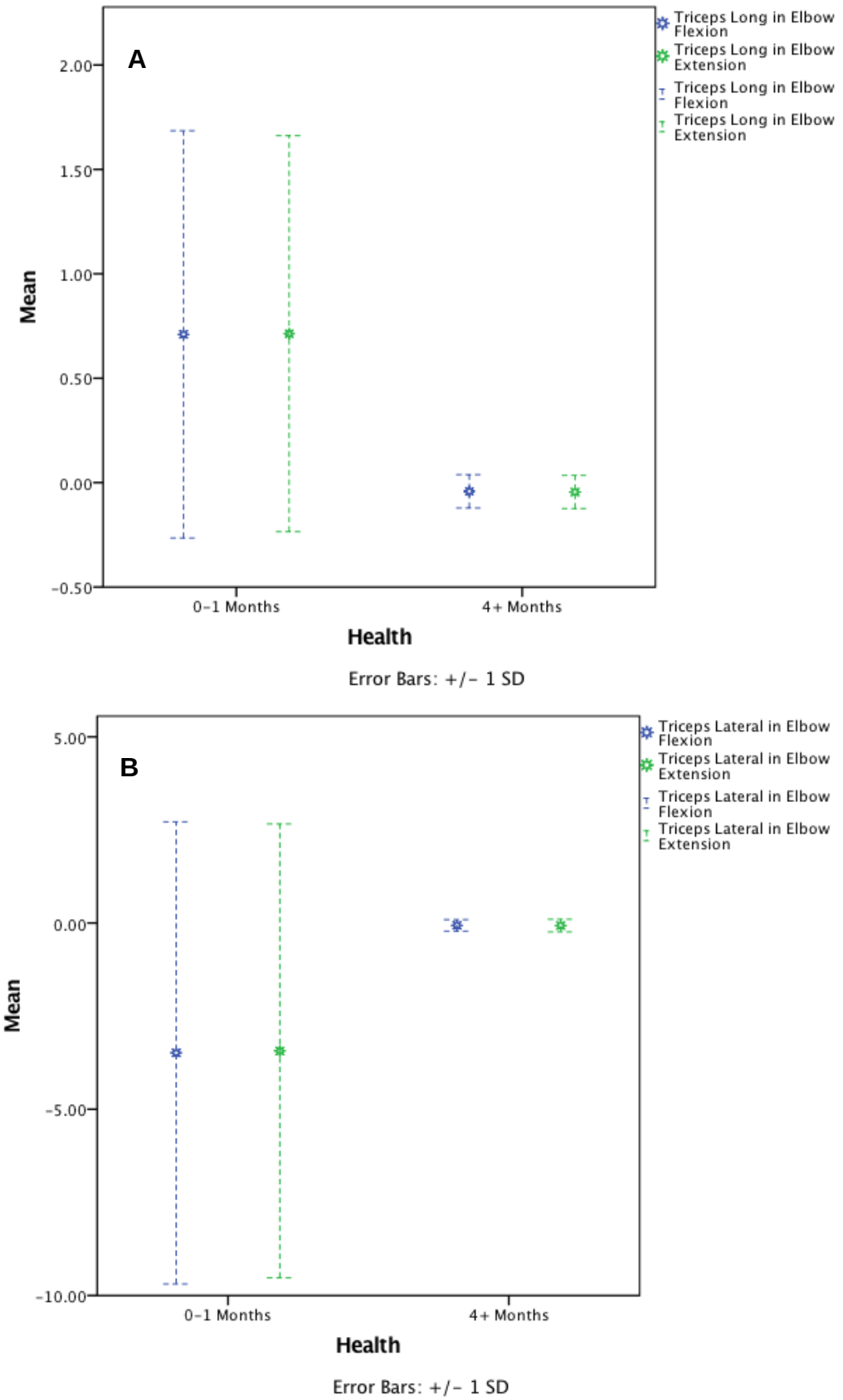


Figure 4.30. MSA measure of TB in EFE (A) and TB2 in EFE (B) motions in early rehab group and late rehab patient group with a standard deviation +/- 1

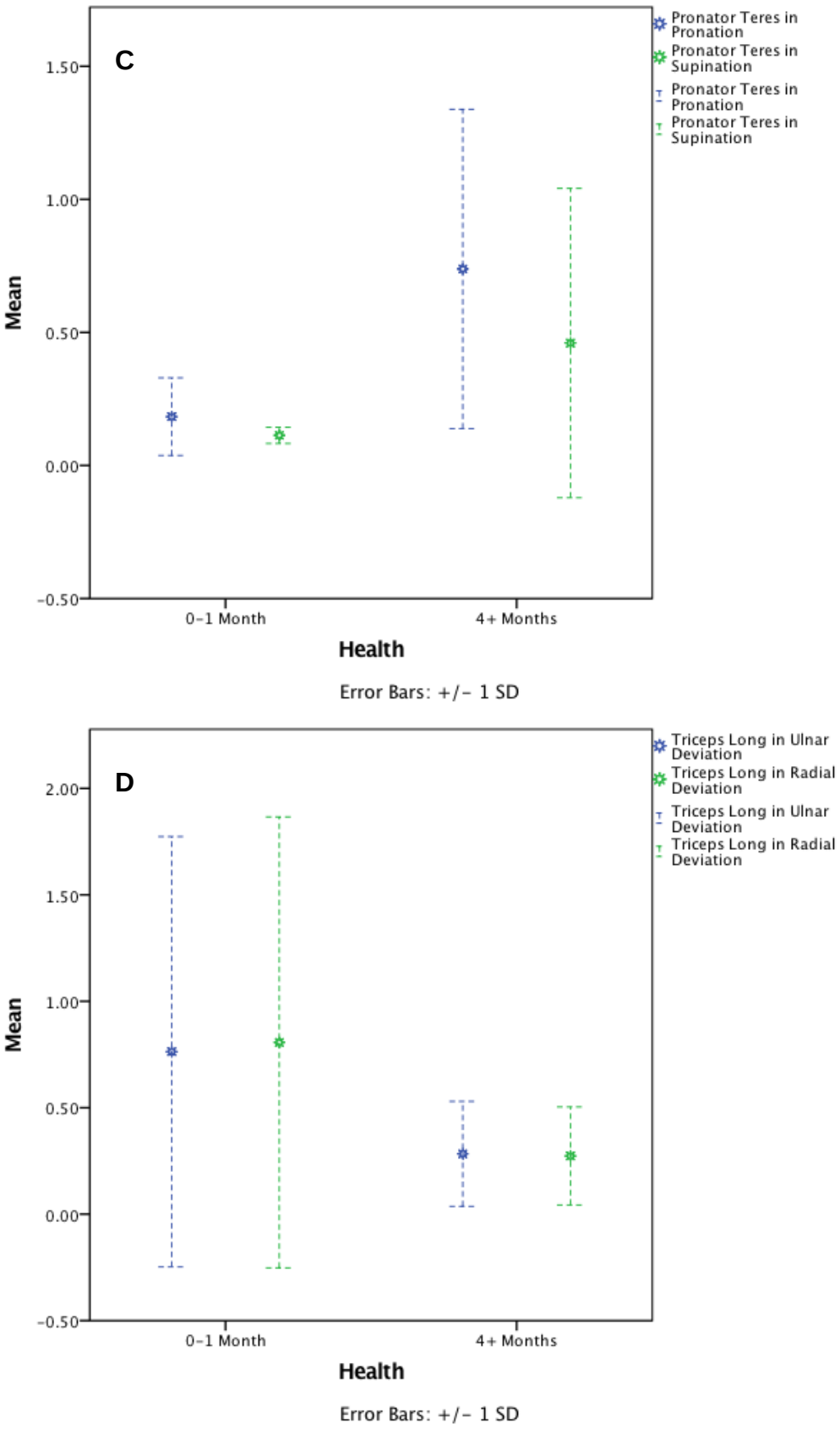


Figure 4.31. MSA measure of PT in PS Pressing (C) and TB in URD (D) motions in early rehab group and late rehab patient group with a standard deviation +/- 1

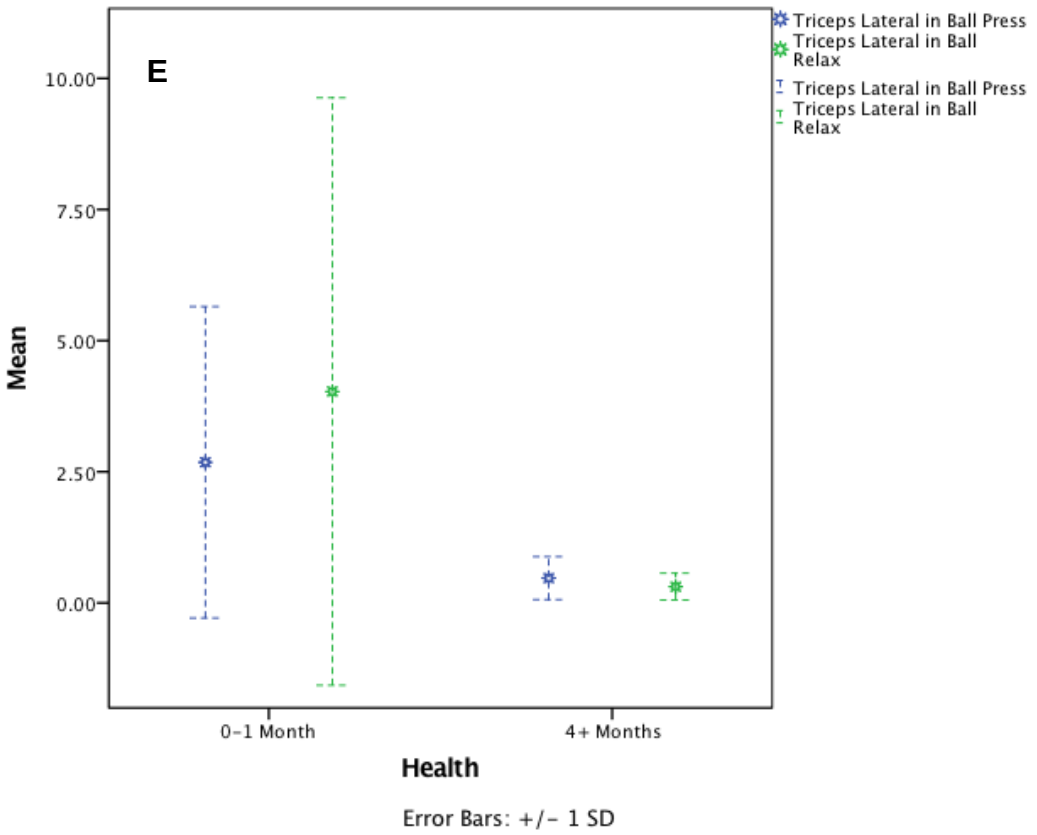


Figure 4.32. MSA measure of TB2 in Ball Pressing (E) motion in early rehab group and late rehab patient group with a standard deviation +/- 1

4.5 PSD

In the frequency domain metrics, there was a general trend showing slightly higher frequencies in the patient population versus the healthy population. Although a lower back pain study showed diagnostic potential of EMG frequency shifts in which it provided valuable information in discriminating between healthy individuals and patients, this was not seen in the trials on the elbow and thus not discussed [50]. For more information, please see Appendix C.

5 Conclusions and Future Work

The work presented in this thesis was aimed at analyzing and characterizing several EMG metrics in order to distinguish an injured person from a healthy person and to determine if an injured patient is healing. A literature search was executed to confirm the gaps in this knowledge of the human body. EMG was readily used to assess neuromuscular health in patients with nerve damage or with neuromuscular diseases such as multiple sclerosis in a clinical setting. In a research setting, EMG has been used to assess levels of activations of a variety of muscles during specific motions. However, EMG has not been used to quantify health, as discussed in this thesis.

The design of the EMG study presented provided a way for deciding if EMG signals can be used to assess health in patients with MSK injuries that do not involve the nerves. This was shown to be true, as statistically significant differences were observed between the healthy and patient group in the first analysis and between the early and late rehabilitation patient groups on various occasions. These differences were observed in the recruitment of MUs of the intended muscles, as well as the hyper-recruitment of muscles not required for the motion to be executed in the patient population. Generally, MU recruitment, firing, and frequency are higher in patients than in healthy individuals.
The knowledge of these general trends of activation is crucial for the use of these signals in the control of a smart rehabilitative brace, such that an activation of a certain muscle is not misinterpreted as an intent to produce a movement in that direction.

Additionally, numerous metrics were explored to identify a metric or a combination of metrics that best assesses people with these MSK conditions. Although frequency domain metrics are very popular in assessing neurological disorders, this was not the case in the studied MSK conditions. The frequencies were shown to be slightly higher in the patient population, but not statistically significant. The time domain metrics explored revealed differences in at least one instance. The best metric to be used cannot yet be determined, as more research with a larger number of subjects would be needed to make this decision. However, RMS seems to show most promise, as it is a reliable metric that exhibited the most statistical significant instances.

5.1 Contributions

This work validates and justifies the use and further exploration of EMG signals as a whole new domain to quantify health. The specific contributions of this work are as follows:

- A creation of a database of EMG signals from patients and healthy individuals that can be used by the control system of a smart rehabilitative brace. This database will allow the control system to make a decision making process based on the data being sensed by the wearer. The information fed into the control system will be used in a decision making process. Consequently, proper assistance required by the wearer according to the level of health they are at will be provided.

- This work has advanced the use of EMG signals beyond the scope of nerve damage. The experiments conducted show that EMG can be used as a method for assessing MSK health. A normal range across the muscle groups has been identified to which the patient population was compared. This showed statistically significant differences in the magnitudes of muscle recruitment and activation between the two groups.

- Furthermore, a comparison within the patient population at the beginning of their therapy versus at the end of their therapy was conducted. Statistical differences arose in this second analysis further proving that patients' signals tend to change and showing trends closer to those of the healthy population.

- Finally, different EMG metrics in the time domain and the frequency domain were explored. Since quantifying health by using EMG in MSK conditions had not been done, the best metric to do so had not been identified. Consequently, numerous metrics were applied in this study to help determine the best metric to be used. Time domain metrics such as RMS, MSA, and ZC, showed the most promise. The frequency domain metrics did not exhibit any differences, and a greater sample size will be required to identify if any of them will be relevant.

5.2 Future Work

This study is by no means completed and it will take a much larger patient cohort to extract all of the relevant information. There are several research possibilities that may be studied in the future, as presented below:

- Collecting data from each patient multiple times across the various months of therapy is the next most important step to be achieved. Due to the time commitment, patients were less willing to continually participate in the study during their follow up visits. A solution to this problem could be to provide an incentive, such as providing them with a monetary value of paying their parking ticket after each completed trial.
- Due to the lack of patient availability, all data collected was combined into one cohort — elbow trauma patients. This included fractures and muscle tears. A more specific study where the types of injuries are separated and analyzed to see if specific injuries demonstrate changes in neuromuscular control and activation should be completed.
- Additionally, a general increase in number of subjects will increase the power of the study. Further trials should be performed to add to the already created database and reassess significance between the groups.
- Although collecting position data using an IMU was attempted in this thesis, most of the data collected was corrupt due to the low RAM of the laptop used. A better computer should be used and position data should be collected in order to detect changes in ROM of the subjects.

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5.3 Appendix A: Ethics Permission and Approvals, Consent Form, and Trial Form

Permissions and Approvals

The following forms and permission statements are presented in this Appendix:

• Ethics approval for the trials on healthy individuals from the Research Ethics Board for Health Sciences Research Involving Human Subjects at the University of Western Ontario
• Ethics approval for the trials on patients from the Research Ethics Board for Health Sciences Research Involving Human Subjects at the University of Western Ontario

Western Research

Research Ethics

Western University Health Science Research Ethics Board
HSREB Full Board Initial Approval Notice

Principal Investigator: Dr. Ana Luisa Trejos
Department & Institution: Unknown,London Health Sciences Centre

Review Type: Full Board
HSREB File Number: 106913
Study Title: Patient Data Collection and Analysis for Elbow Smart Brace
Sponsor: Natural Sciences and Engineering Research Council

HSREB Initial Approval Date: October 01, 2015
HSREB Expiry Date: October 01, 2016

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Instruments		2015/06/23
Western University Protocol		2015/09/21
Letter of Information & Consent		2015/09/01

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Western Research

Research Ethics

Western University Health Science Research Ethics Board
HSREB Annual Continuing Ethics Approval Notice

Date: August 18, 2015
Principal Investigator: Dr. Ana Luisa Trejos
Department & Institution: Unknown,London Health Sciences Centre

Review Type: Expedited
HSREB File Number: 105717
Study Title: EMG-driven Model for Motion Prediction
Sponsor: Natural Sciences and Engineering Research Council

HSREB Renewal Due Date & HSREB Expiry Date:
Renewal Due -2016/09/30
Expiry Date -2016/10/06

The Western University Health Science Research Ethics Board (HSREB) has reviewed the Continuing Ethics Review (CER) Form and is re-issuing approval for the above noted study.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice (ICH E6 R1), the Ontario Freedom of Information and Protection of Privacy Act (FIPPA, 1990), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

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Letter of Information

Title: Patient Data Collection and Analysis for an Elbow Smart Brace

Dr. Ana Luisa Trejos, Ph.D., P.Eng (Principal Investigator)
Assistant Professor, Department of Electrical and Computer Engineering

[redacted]

Shrikant Chinchalkar, (Co-Investigator)
Therapist, Schulich School of Medicine and Dentistry

[redacted]

Raneem Haddara, M.E.Sc. Candidate (Coordinator)
Graduate Student, Biomedical Engineering Program

[redacted]

Myles Lidka, M.E.Sc. Candidate (Coordinator)
Graduate Student, Electrical Engineering Program

[redacted]

Please Initial:_____

Abelardo Escoto, M.E.Sc. (Coordinator)
Associate Researcher, Canadian Surgical Technologies & Advanced Robotics (CSTAR)

[redacted]

Dr. Evan Friedman (Industry Sponsor/Collaborator)
Intronix Technologies Corporation

[redacted]

Sponsor Information:

Intronix Technologies Corporation designs and produces progressive portable medical devices for neuromuscular diagnostics and treatment delivery. Its innovations in injection guidance provide technology that drives clinical solutions to deliver confidence, improve workflow efficiency, and provide a better patient experience. Intronix has extensive experience within the neuromuscular diagnostic and treatment delivery market. Intronix quality system is registered to both ISO 9001:2008 and ISO 13485:2003 (CMDCAS), and is fully USFDA compliant.

For this project, Intronix has lent the WearME Lab their electromyography data collection system and is developing software that will help with improved data collection strategies. All of the data analysis will be performed at the WearMe Lab. Some data samples will need to be sent to Intronix so that they can fine-tune the software to improve the data collection

Conflict of Interest:

There are no real or perceived conflicts of interest in this study.

Details of the Study:

You are being invited to participate in this research study about collecting muscular activity signals because you have a musculoskeletal injury or disorder in your arm.

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Musculoskeletal Conditions cost the Canadian health care system over $17 billion yearly. The purpose of this study is to create a reference base of task-specific bio-signals of people's arm motions in order to inform the development of smart rehabilitation technologies (smart braces). Our smart brace, the WearMe Brace, is a rigid brace in development for the purpose of supporting a patient's weak or deformed arm to enable functional activities. In order to enhance in the development of the brace, muscle activity data will be collected and analyzed to determine how muscle activity changes when the muscles heal. This will provide more intuitive and interpretable information for the control system of the smart brace. The results of the trials will provide valuable information for future improvements of the brace, such that it can provide therapy and assist individuals with upper arm musculoskeletal conditions.

You are being asked to participate because you have a musculoskeletal injury or disorder in your arm. Your usual standard of care will not be altered.

Up to 300 people will participate in this study and it will take 1 year to complete. It is expected that you will be in this study throughout the length of your treatment, until you fully recover (rehabilitation time is different from patient to patient).

Study Design and Procedures:

The experiments will be conducted at the Hand Therapy Clinic at Saint Joseph's Hospital. If you agree to participate, you will be first asked to sign the consent form. You will also be asked to fill out a self-reported trial form with your personal information as follows: age, gender, weight, height, and hand dominance. After that, a research coordinator will measure the dimensions of your arm. The one-time collection of such personal information is required because muscle activity is intimately related to these characteristics and being able to relate the data to these baseline values is critical for proper analysis.

You will then be asked to sit down on a chair. Surface electrodes (small sensors) will be placed on the skin overlying each muscle or group of muscles in the upper arm and forearm (using sticky pads). These sensors do not obstruct normal movement and are not invasive. The skin where the sensors will be placed will be cleaned with alcohol. As the alcohol vaporizes, two electrodes will be placed on the biceps, four on the triceps, and four on the forearm.

You will then be directed to perform the exercises prescribed by your hand therapist in his or her presence and guidance. The therapy normally provided by the therapist will not be modified. The activity of the arm muscles will be recorded during the tasks using the surface

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electrodes. A video camera will record the motions of your arm as you are performing the exercises. Your face will not appear in the frame of the camera at any time.

If your other arm is healthy and uninjured, you will be asked to participate in a one-time trial. If you agree, surface electrodes will also be placed on that arm. You will then be asked to put your arm in an adjustable mechanical brace. Your arm will then be secured to the brace using padded straps. The brace limits the arm motion in one of your natural directions of motion. You will be asked to hold a 5-pound weight on your hand and will be instructed to perform elbow flexion-extension tasks (biceps-curls) requiring you to move your lower arm through a specified range at a low speed. You will perform 3 sets of 3 repetitions at 6 different ranges of motion (for a total of 54 repetitions), with a 2-minute break in between sets. We will measure arm motion and muscle activity while you perform these tasks. You will be given a few trial runs to help you learn and understand the process and the speed required for the motions. This experiment is a one-time process and you will not be asked to do it again during your next visits. It is estimated to take up to 45 minutes for this one-time experiment.

Your participation in this study is voluntary. You may decide not to be in this study, or to be in the study now and then change your mind later. You may leave the study at any time without affecting your care. We will give you new information that is learned during the study that might affect your decision to stay in the study.

Withdrawal:

If you decide to withdraw from the study, the information that was collected before you leave will still be used in order to help answer the research question. No new information will be collected without your permission.

Risks:

There are no added risks to you since you will be performing what your hand therapist is prescribing you to do.

For the healthy arm, there may be temporary muscle discomfort/fatigue due to the tasks being performed. The mechanical brace will limit your motion in a single plane, which is one of your natural motion directions. The operation can be stopped immediately at any time you wish. The loads for the trial are comparable to the weight of a textbook.

Benefits:

There are no direct benefits to you by participating in this study. Although you may not benefit directly from this study, your participation may contribute to our basic knowledge of human

Please Initial:_____

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mechanical dynamics, human muscle recruitment, and how to incorporate this knowledge into improving the treatment of musculoskeletal disorders. It will also allow us to advance in the development of a mechatronics-enabled elbow brace in our lab through tuning the system and using the data to allow the brace to provide individualized therapy to its wearers.

Confidentiality:

Confidentiality cannot be 100% guaranteed. All data will be stored in password-protected personal computer (University of Western Ontario, Spencer Engineering Building, Room 2091). Hardcopies of any documents will be stored in locked cabinets in TEB 373. The only documents containing your name will be the Consent Forms, which will not be linked to any of the recorded data. Access to records and data is limited to authorized persons.

Qualified representatives of the following organizations may look at your study records at the site where these records are held, for quality assurance (to check that the information collected for the study is correct and follows proper laws and guidelines).

Examples include:

- Representatives of Lawson Quality Assurance Education Program
- Representatives of University of Western Ontario Health Sciences Research Ethics Board that oversees the ethical conduct of this study.
- Representatives of Health Canada or other regulatory bodies (groups of people who oversee research studies) outside of Canada, such as the United States food and Drug Administration.
- Intronix Technologies Corporation and its affiliated companies

Some of the muscle activity data collected will be transferred to Intronix Technologies Corporation by using an encrypted USB hard drive in order to improve the data collection software. Your anonymity will be protected through the use of alphanumeric codes when analyzing your experimental data.

This project is supported by a Discovery Grant and an Engage grant of the Natural Sciences and Engineering Research Council (NSERC) of Canada, by the Western Strategic Support for NSERC Success Grant, by the Academic Development Fund, Western University, and by the Ontario Centres of Excellence with support from Intronix Technologies Corporation.

Please Initial:_____

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If you have any questions or concerns regarding participation in our study, please contact Dr. Ana Luisa Trejos at ([redacted], email: [redacted]
If you have any questions about the conduct of this study or your rights as a research subject you may contact Dr. David Hill, Scientific Director, Lawson Health Research Institute at [redacted] A copy of this information package is yours to keep for your personal records.

Please Initial:_____

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CONSENT FORM

Title of Research:	**Title: Patient Data Collection and Analysis for an Elbow Smart Brace**
Principal Investigator:	Dr. Ana Luisa Trejos
Co-Investigators:	Shrikant Chinchalkar
Collaborators:	Raneem Haddara, Myles Lidka, Abelardo Escoto, and Intronix Technologies Corporation

For the Participant:

I have read and understand the above information describing this study. I have had the purposes, procedures and technical language of this study explained to me. I have been given sufficient time to consider the above information and to seek advice if I chose to do so. I have had the opportunity to ask questions which have been answered to my satisfaction. I am voluntarily signing this form. I will receive a copy of this consent form for my information.

If at any time I have further questions, problems or adverse events, I can contact Dr. Ana Luisa Trejos, the principal investigator of the project, at [redacted]1 or any of the investigators and collaborators on the project.

If I have any questions about the conduct of this study or your rights as a research subject I may contact Dr. David Hill, Scientific Director, Lawson Health Research Institute at [redacted]

By signing this consent form, I am indicating that I agree to participate in this study.

_____	_____	_____
Name of Participant (Please print)	**Signature of Participant**	**Date**
_____	_____	_____
Name of Person Obtaining Informed Consent	**Signature of Person Obtaining Informed Consent**	**Date**

Please Initial:_____

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TRIAL FORM

Title of Research:	**Patient Data Collection and Analysis for a Mechatronics Brace**
Principal Investigator:	Dr. Ana Luisa Trejos
Co-Investigators:	Shrikant Chinchalkar and Dr. Evan Friedman
Coordinators:	Raneem Haddara, Myles Lidka, Abelardo Escoto

To be filled out by the Participant:

If you are not comfortable answering any of these questions, you do not have to respond.

Age: _____
Dominant hand: R L
Gender: M F

Weight: _____ kg
Height: _____ cm

To be measured and entered by the Coordinator:

Upper arm length: _____mm
Forearm length: _____mm
Hand length: _____ mm

Upper arm circumference: _____mm
Forearm circumference: _____ mm
Hand circumference: _____mm

Subject code: _____

5.4 Appendix B: MATLAB Code

This appendix will represent the MATLAB functions for one channel for simplicity.

```
%%Channel Information

%CHANNEL 1 Biceps

%MOTION
channel_1_0 = record(1,:);
channel_1= channel_1_0-mean(channel_1_0(1,1:10)); %%%%%%%%%%
t1 = 1:numel(channel_1_0);
rms_channel_1_0 = rms(channel_1_0);
N1=length(channel_1_0);
y2_1=detrend(channel_1_0);
rec_y_1=abs(y2_1);
[b,a]=butter(5,1/2000,'low');
filter_y_1=filtfilt(b,a,rec_y_1);


%BB MVC
channel_1_2 = record2(1,:);
channel_1_2_BB=(channel_1_2-mean(channel_1_2(1,1:10))); %%%%%%%%%%;
t1_2 = 1:numel(channel_1_2);
rms_channel_1_2 = rms(channel_1_2);
N2=length(channel_1_2);
y2_1_=detrend(channel_1_2_BB);
rec2_y_1=abs(y2_1_);
[b,a]=butter(5,1/2000,'low');
filter2_y_1=filtfilt(b,a,rec2_y_1);
BBmax=max(rec2_y_1);
BBmin=min(rec2_y_1);
Norm_BB=(channel_1-BBmin)/(BBmax-BBmin);


%TB MVC
channel_1_3 = record3(1,:);
channel_1_3_TB= (channel_1_3 -mean(channel_1_3(1,1:10))); %%%%%%
t1_3 = 1:numel(channel_1_3);
rms_channel_1_3 = rms(channel_1_3);
N3=length(channel_1_3);
y2_1__=detrend(channel_1_3_TB);
rec3_y_1=abs(y2_1__);
[b,a]=butter(5,1/2000,'low');
filter3_y_1=filtfilt(b,a,rec3_y_1);

%% Graph Plotting

% Channel 1
figure('name','Raw/Rectified/Low Pass of Biceps','numbertitle','off')

subplot (5,1,1), plot (t1,channel_1)
xlabel('Sample Number')
ylabel('Raw EMG')

subplot(5,1,2), plot(rec_y_1)
```

```
xlabel('sample number')
ylabel('rectified EMG signal')

subplot(5,1,3), plot(filter_y_1)
xlabel('Sample Number')
ylabel('Low Pass Filtered EMG Signal')

subplot (5,1,4), plot (t1_2,channel_1_2_BB)
xlabel('Sample Number')
ylabel('BB MVC Raw')

subplot(4,1,4), plot(Norm_BB)
xlabel('Sample Number')
ylabel('Normalized')
% %
% Flexion:
Start1_1 = ginput(1)
End1_1 = ginput(1)
Start2_1 = ginput(1)
End2_1 = ginput(1)
Start3_1 = ginput(1)
End3_1 = ginput(1)

% Extension:
Start1_2 = ginput(1)
End1_2 = ginput(1)
Start2_2 = ginput(1)
End2_2 = ginput(1)
Start3_2 = ginput(1)
End3_2 = ginput(1)




%% Mean RMS Rep Calculation

% Subject Mean Biceps Channel Flexion 1 RMS
Rep1_1_0_BB_1= rms(channel_1(round(Start1_1):round(End1_1)))
Rep2_1_0_BB_1= rms(channel_1(round(Start2_1):round(End2_1)))
Rep3_1_0_BB_1= rms(channel_1(round(Start3_1):round(End3_1)))

Mean_RMS_BB_1=(Rep1_1_0_BB_1+Rep2_1_0_BB_1+Rep3_1_0_BB_1)/3

% Subject Mean Biceps Channel Extension 1 RMS
Rep1_1_0_BB_2= rms(channel_1(round(Start1_2):round(End1_2)))
Rep2_1_0_BB_2= rms(channel_1(round(Start2_2):round(End2_2)))
Rep3_1_0_BB_2= rms(channel_1(round(Start3_2):round(End3_2)))

Mean_RMS_BB_2=(Rep1_1_0_BB_2+Rep2_1_0_BB_2+Rep3_1_0_BB_2)/3
```

```
%% Mean Average Rectified Value


% Subject Mean Biceps Channel Flexion 1 RMS
Rep1_1_0_BB_1_ARV= mean(rec_y_ 1(round(Start1_1):round(End1_1)))
Rep2_1_0_BB_1_ARV= mean(rec_y_1(round(Start2_1):round(End2_1)))
Rep3_1_0_BB_1_ARV= mean(rec_y_1(round(Start3_1):round(End3_1)))

Mean_RMS_BB_1_ARV=(Rep1_1_0_BB_1_ARV+Rep2_1_0_BB_1_ARV+Rep3_1_0_BB_1_AR
V)/3

% Subject Mean Biceps Channel Extension 1 RMS
Rep1_1_0_BB_2_ARV= mean(rec_y_1(round(Start1_2):round(End1_2)))
Rep2_1_0_BB_2_ARV= mean(rec_y_1(round(Start2_2):round(End2_2)))
Rep3_1_0_BB_2_ARV= mean(rec_y_1(round(Start3_2):round(End3_2)))

Mean_RMS_BB_2_ARV=(Rep1_1_0_BB_2_ARV+Rep2_1_0_BB_2_ARV+Rep3_1_0_BB_2_AR
V)/3

%% Mean MSA Rep Calculation

% Subject Mean Biceps Channel Flexion 1 MSA


Rep1_1_0_BB_MSA=(channel_1(round(Start1_1):round(End1_1)))

[pks,locs]=findpeaks(Rep1_1_0_BB_MSA,'MINPEAKDISTANCE',50);
% figure
% plot(t5_2,channel_1,'r', t5_2(locs),pks,'*')    % show peaks on top
of the EMG data

SA_1_1_1=[];
for i=1:1:length(locs)-1 %
if min(Rep1_1_0_BB_MSA(locs(i):locs(i+1)))<0 && pks(i)>0 && pks(i+1)
    temp=((pks(i)-min(Rep1_1_0_BB_MSA(locs(i):locs(i+1))))+(pks(i+1)-
min(Rep1_1_0_BB_MSA(locs(i):locs(i+1)))))/2;
         SA_1_1_1=[SA_1_1_1,temp];
end
 MSA_ch1_rep1_1=mean(SA_1_1_1);
end


Rep2_1_0_BB_MSA=(channel_1(round(Start2_1):round(End2_1)));


[pks,locs]=findpeaks(Rep2_1_0_BB_MSA,'MINPEAKDISTANCE',50);
% figure
% plot(t5_2,channel_1,'r', t5_2(locs),pks,'*')    % show peaks on top
of the EMG data

SA_1_2_1=[];
for i=1:1:length(locs)-1 %
if min(Rep2_1_0_BB_MSA(locs(i):locs(i+1)))<0 && pks(i)>0 && pks(i+1)
```

```
    temp=((pks(i)-min(Rep2_1_0_BB_MSA(locs(i):locs(i+1))))+(pks(i+1)-
min(Rep2_1_0_BB_MSA(locs(i):locs(i+1)))))/2;
         SA_1_2_1=[SA_1_2_1,temp];
end
 MSA_ch1_rep2_1=mean(SA_1_2_1);
end

Rep3_1_0_BB_MSA=(channel_1(round(Start3_1):round(End3_1)));


[pks,locs]=findpeaks(Rep3_1_0_BB_MSA,'MINPEAKDISTANCE',50);
% figure
% plot(t5_2,channel_1,'r', t5_2(locs),pks,'*')    % show peaks on top
of the EMG data

SA_1_3_1=[];
for i=1:1:length(locs)-1 %
if min(Rep3_1_0_BB_MSA(locs(i):locs(i+1)))<0 && pks(i)>0 && pks(i+1)
    temp=((pks(i)-min(Rep3_1_0_BB_MSA(locs(i):locs(i+1))))+(pks(i+1)-
min(Rep3_1_0_BB_MSA(locs(i):locs(i+1)))))/2;
         SA_1_3_1=[SA_1_3_1,temp];
end
 MSA_ch1_rep3_1=mean(SA_1_3_1);
end


Mean_MSA_BB_1_MSA=(mean(SA_1_1_1)+mean(SA_1_2_1)+mean(SA_1_3_1))/3;

% Subject Mean Biceps Channel Extension 1 MSA


Rep1_1_0_BB_2_MSA= (channel_1(round(Start1_2):round(End1_2)));


[pks,locs]=findpeaks(Rep1_1_0_BB_2_MSA,'MINPEAKDISTANCE',50);
% figure
% plot(t5_2,channel_1,'r', t5_2(locs),pks,'*')    % show peaks on top
of the EMG data

SA_1_1_2=[];
for i=1:1:length(locs)-1 %
if min(Rep1_1_0_BB_2_MSA(locs(i):locs(i+1)))<0 && pks(i)>0 && pks(i+1)
    temp=((pks(i)-min(Rep1_1_0_BB_2_MSA(locs(i):locs(i+1))))+(pks(i+1)-
min(Rep1_1_0_BB_2_MSA(locs(i):locs(i+1)))))/2;
         SA_1_1_2=[SA_1_1_2,temp];
end
 MSA_ch1_rep1_2=mean(SA_1_1_2);
end


Rep2_1_0_BB_2_MSA=(channel_1(round(Start2_2):round(End2_2)));

[pks,locs]=findpeaks(Rep2_1_0_BB_2_MSA,'MINPEAKDISTANCE',50);
% figure
% plot(t5_2,channel_1,'r', t5_2(locs),pks,'*')    % show peaks on top
of the EMG data
```

```
SA_1_2_2=[];
for i=1:1:length(locs)-1 %
if min(Rep2_1_0_BB_2_MSA(locs(i):locs(i+1)))<0 && pks(i)>0 && pks(i+1)
    temp=((pks(i)-min(Rep2_1_0_BB_2_MSA(locs(i):locs(i+1))))+(pks(i+1)-
min(Rep2_1_0_BB_2_MSA(locs(i):locs(i+1)))))/2;
        SA_1_2_2=[SA_1_2_2,temp];
end
 MSA_ch1_rep2_2=mean(SA_1_2_2);
end

Rep3_1_0_BB_2_MSA=(channel_1(round(Start3_2):round(End3_2)));


[pks,locs]=findpeaks(Rep3_1_0_BB_2_MSA,'MINPEAKDISTANCE',50);
% figure
% plot(t5_2,channel_1,'r', t5_2(locs),pks,'*')    % show peaks on top
of the EMG data

SA_1_3_2=[];
for i=1:1:length(locs)-1 %
if min(Rep3_1_0_BB_2_MSA(locs(i):locs(i+1)))<0 && pks(i)>0 && pks(i+1)
    temp=((pks(i)-min(Rep3_1_0_BB_2_MSA(locs(i):locs(i+1))))+(pks(i+1)-
min(Rep3_1_0_BB_2_MSA(locs(i):locs(i+1)))))/2;
        SA_1_3_2=[SA_1_3_2,temp];
end
 MSA_ch1_rep3_2=mean(SA_1_3_2);
end


Mean_MSA_BB_2_MSA=(mean(SA_1_1_2)+mean(SA_1_2_2)+mean(SA_1_3_2))/3;


%% Number of Zero Crossings

%Channel 1 Biceps

%Rep1
ZC_1_1_1=0;
count_1_1_1 =sign(channel_1(round(Start1_1):round(End1_1)));
NZ= length(count_1_1_1);
for i=1:1:NZ-1
if count_1_1_1(i+1)~= count_1_1_1(i);
    ZC_1_1_1 = ZC_1_1_1+1;
end
end


%Rep2
ZC_1_2_1=0;
count_1_2_1 =sign(channel_1(round(Start2_1):round(End2_1)));
NZ= length(count_1_2_1);
for i=1:1:NZ-1
if count_1_2_1(i+1)~= count_1_2_1(i);
    ZC_1_2_1 = ZC_1_2_1+1;
end
end
```

```
%Rep3

ZC_1_3_1=0;
count_1_3_1 =sign(channel_1(round(Start3_1):round(End3_1)));
NZ= length(count_1_3_1);
for i=1:1:NZ-1
if count_1_3_1(i+1)~= count_1_3_1(i);
    ZC_1_3_1 = ZC_1_3_1+1;
end
end


mean_ZC_1_1= (ZC_1_1_1+ZC_1_2_1+ZC_1_3_1)/3;


%Rep1
ZC_1_1_2=0;
count_1_1_2 =sign(channel_1(round(Start1_2):round(End1_2)));
NZ= length(count_1_1_2);
for i=1:1:NZ-1
if count_1_1_2(i+1)~= count_1_1_2(i);
    ZC_1_1_2 = ZC_1_1_2+1;
end
end


%Rep2
ZC_1_2_2=0;
count_1_2_2 =sign(channel_1(round(Start2_2):round(End2_2)));
NZ= length(count_1_2_2);
for i=1:1:NZ-1
if count_1_2_2(i+1)~= count_1_2_2(i);
    ZC_1_2_2 = ZC_1_2_2+1;
end
end

%Rep3

ZC_1_3_2=0;
count_1_3_2 =sign(channel_1(round(Start3_2):round(End3_2)));
NZ= length(count_1_3_2);
for i=1:1:NZ-1
if count_1_3_2(i+1)~= count_1_3_2(i);
    ZC_1_3_2 = ZC_1_3_2+1;
end
end


mean_ZC_1_2= (ZC_1_1_2+ZC_1_2_2+ZC_1_3_2)/3;


%% Power Spectral Density Analysis
P_1_1_1=fft (channel_1);
P_1_1_1=abs(P_1_1_1);
f=(0:N1-1)/(step*N1);
Fs=1/samplef;
windowsize = 1500;
```

```
window = hanning(windowsize);
nfft = windowsize;
noverlap = windowsize-1;


%Channel 1 Flexion

%Rep 1
tempP_1_1_1=[];
[S_1_1_1,F_1_1_1,T_1_1_1,P_1_1_1] =
spectrogram(channel_1(round(Start1_1(1)):round(End1_1(1))),window,nover
lap,nfft,1/Fs);

for i=1:1:length(P_1_1_1(:,1))    % fat to slim
tempP_1_1_1=[tempP_1_1_1; P_1_1_1(i,:)'];
end
if rem(length(tempP_1_1_1),2)==1

Median_Freq_1_1_1=F_1_1_1(floor(find(tempP_1_1_1==median(tempP_1_1_1))/
length(P_1_1_1(1,:))));
else
Median_Freq_1_1_1=F_1_1_1(floor(find(tempP_1_1_1(1:end-
1)==median(tempP_1_1_1(1:end-1)))/length(P_1_1_1(1,1:end-1))));
end
% rem(find(tempP_1_1_1==median(tempP_1_1_1)),length(P_1_1_1(1,:)));  %
remainder

[idx_1_1_1, idx_1_1_1] = min(abs(tempP_1_1_1-mean(tempP_1_1_1)));
%index of closest value
Mean_Freq_1_1_1 = F_1_1_1(floor(idx_1_1_1/length(P_1_1_1(1,:))));
%closest value


%Rep 2
tempP_1_2_1=[];
[S_1_2_1,F_1_2_1,T_1_2_1,P_1_2_1] =
spectrogram(channel_1(round(Start2_1(1)):round(End2_1(1))),window,nover
lap,nfft,1/Fs);

for i=1:1:length(P_1_2_1(:,1))    % fat to slim
tempP_1_2_1=[tempP_1_2_1; P_1_2_1(i,:)'];
end
if rem(length(tempP_1_2_1),2)==1

Median_Freq_1_2_1=F_1_2_1(floor(find(tempP_1_2_1==median(tempP_1_2_1))/
length(P_1_2_1(1,:))));
else
Median_Freq_1_2_1=F_1_2_1(floor(find(tempP_1_2_1(1:end-
1)==median(tempP_1_2_1(1:end-1)))/length(P_1_2_1(1,1:end-1))));
end
% rem(find(tempP_1_1_1==median(tempP_1_1_1)),length(P_1_1_1(1,:)));  %
remainder

[idx_1_2_1, idx_1_2_1] = min(abs(tempP_1_2_1-mean(tempP_1_2_1)));
%inde2 of closest value
Mean_Freq_1_2_1 = F_1_2_1(floor(idx_1_2_1/length(P_1_2_1(1,:))));
%closest value
```

```
%Rep 3
tempP_1_3_1=[];
[S_1_3_1,F_1_3_1,T_1_3_1,P_1_3_1] =
spectrogram(channel_1(round(Start3_1(1)):round(End3_1(1))),window,nover
lap,nfft,1/Fs);

for i=1:1:length(P_1_3_1(:,1))    % fat to slim
tempP_1_3_1=[tempP_1_3_1; P_1_3_1(i,:)'];
end
if rem(length(tempP_1_3_1),2)==1

Median_Freq_1_3_1=F_1_3_1(floor(find(tempP_1_3_1==median(tempP_1_3_1))/
length(P_1_3_1(1,:))));
else
Median_Freq_1_3_1=F_1_3_1(floor(find(tempP_1_3_1(1:end-
1)==median(tempP_1_3_1(1:end-1)))/length(P_1_3_1(1,1:end-1))));
end
% rem(find(tempP_1_1_1==median(tempP_1_1_1)),length(P_1_1_1(1,:)));  %
remainder

[idx_1_3_1, idx_1_3_1] = min(abs(tempP_1_3_1-mean(tempP_1_3_1)));
%inde3 of closest value
Mean_Freq_1_3_1 = F_1_3_1(floor(idx_1_3_1/length(P_1_3_1(1,:))));
%closest value


%Channel 1 Extension

%Rep 1
tempP_1_1_2=[];
[S_1_1_2,F_1_1_2,T_1_1_2,P_1_1_2] =
spectrogram(channel_1(round(Start1_2(1)):round(End1_2(1))),window,nover
lap,nfft,1/Fs);

for i=1:1:length(P_1_1_2(:,1))    % fat to slim
tempP_1_1_2=[tempP_1_1_2; P_1_1_2(i,:)'];
end
if rem(length(tempP_1_1_2),2)==1

Median_Freq_1_1_2=F_1_1_2(floor(find(tempP_1_1_2==median(tempP_1_1_2))/
length(P_1_1_2(1,:))));
else
Median_Freq_1_1_2=F_1_1_2(floor(find(tempP_1_1_2(1:end-
1)==median(tempP_1_1_2(1:end-1)))/length(P_1_1_2(1,1:end-1))));
end
% rem(find(tempP_1_1_1==median(tempP_1_1_1)),length(P_1_1_1(1,:)));  %
remainder

[idx_1_1_2, idx_1_1_2] = min(abs(tempP_1_1_2-mean(tempP_1_1_2)));
%inde1 of closest value
Mean_Freq_1_1_2 = F_1_1_2(floor(idx_1_1_2/length(P_1_1_2(1,:))));
%closest value

%Rep 2
tempP_1_2_2=[];
```

```
[S_1_2_2,F_1_2_2,T_1_2_2,P_1_2_2] =
spectrogram(channel_1(round(Start2_2(1)):round(End2_2(1))),window,nover
lap,nfft,1/Fs);

for i=1:1:length(P_1_2_2(:,1))    % fat to slim
tempP_1_2_2=[tempP_1_2_2; P_1_2_2(i,:)'];
end
if rem(length(tempP_1_2_2),2)==1

Median_Freq_1_2_2=F_1_2_2(floor(find(tempP_1_2_2==median(tempP_1_2_2))/
length(P_1_2_2(1,:))));
else
Median_Freq_1_2_2=F_1_2_2(floor(find(tempP_1_2_2(1:end-
1)==median(tempP_1_2_2(1:end-1)))/length(P_1_2_2(1,1:end-1))));
end
% rem(find(tempP_1_1_1==median(tempP_1_1_1)),length(P_1_1_1(1,:)));  %
remainder

[idx_1_2_2, idx_1_2_2] = min(abs(tempP_1_2_2-mean(tempP_1_2_2)));
%inde2 of closest value
Mean_Freq_1_2_2 = F_1_2_2(floor(idx_1_2_2/length(P_1_2_2(1,:))));
%closest value

%Rep 3
tempP_1_3_2=[];
[S_1_3_2,F_1_3_2,T_1_3_2,P_1_3_2] =
spectrogram(channel_1(round(Start3_2(1)):round(End3_2(1))),window,nover
lap,nfft,1/Fs);

for i=1:1:length(P_1_3_2(:,1))    % fat to slim
tempP_1_3_2=[tempP_1_3_2; P_1_3_2(i,:)'];
end
if rem(length(tempP_1_3_2),2)==1

Median_Freq_1_3_2=F_1_3_2(floor(find(tempP_1_3_2==median(tempP_1_3_2))/
length(P_1_3_2(1,:))));
else
Median_Freq_1_3_2=F_1_3_2(floor(find(tempP_1_3_2(1:end-
1)==median(tempP_1_3_2(1:end-1)))/length(P_1_3_2(1,1:end-1))));
end
% rem(find(tempP_1_1_1==median(tempP_1_1_1)),length(P_1_1_1(1,:)));  %
remainder

[idx_1_3_2, idx_1_3_2] = min(abs(tempP_1_3_2-mean(tempP_1_3_2)));
%inde3 of closest value
Mean_Freq_1_3_2 = F_1_3_2(floor(idx_1_3_2/length(P_1_3_2(1,:))));
%closest value
```

5.5 Appendix C: Statistical Analyses Tables

The following section shows comparisons of the healthy population to the patient population.

Table C.1 RMS statistical analysis between patients and healthy individuals in 6 motions

Metric	Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
RMS	EFE	BB	0.16832	0.22059	0.065	0.059	0.557	0.353
RMS	EFE	TB	0.238	0.519	0.157	0.142	0.196	1.76
RMS	EFE	TB2	0.085	0.14	0.035	0.031	0.315	1.371
RMS	EFE	PT	0.083	0.084	0.022	0.02	0.973	0.001
RMS	EFE	FCU	0.085	0.14	0.035	0.031	0.252	1.371
RMS	**EFE**	**ECU**	**0.021**	**0.104**	**0.028**	**0.025**	**0.037**	**4.836**
RMS	PS	BB	0.096	0.101	0.025	0.024	0.905	0.015
RMS	PS	TB	0.134	0.38	0.105	0.102	0.102	2.844
RMS	PS	TB2	0.054	0.084	0.025	0.024	0.394	0.749
RMS	**PS**	**PT**	**0.028**	**0.103**	**0.023**	**0.023**	**0.028**	**5.348**
RMS	PS	FCU	0.023	0.071	0.017	0.017	0.053	4.049
RMS	**PS**	**ECU**	**0.015**	**0.095**	**0.019**	**0.018**	**0.005**	**9.281**
RMS	WFE	BB	0.065	0.102	0.019	0.02	0.194	1.792
RMS	WFE	TB	0.092	0.282	0.092	0.1	0.176	1.956
RMS	WFE	TB2	0.026	0.162	0.059	0.064	0.13	2.479
RMS	WFE	PT	0.033	0.063	0.016	0.017	0.22	1.594
RMS	WFE	FCU	0.043	0.135	0.04	0.044	0.141	2.334
RMS	WFE	ECU	0.034	0.119	0.028	0.031	0.053	4.195
RMS	URD	BB	0.069	0.137	0.029	0.027	0.096	2.977
RMS	URD	TB	0.101	1.58	0.961	0.894	0.27	1.27
RMS	URD	TB2	0.029	1.18	0.875	0.814	0.345	0.927
RMS	URD	PT	0.043	0.047	0.013	0.013	0.09	3.106
RMS	URD	FCU	0.021	0.072	0.019	0.018	0.062	3.793
RMS	URD	ECU	0.029	0.294	0.142	0.132	0.183	1.876
RMS	HOC	BB	0.085	0.143	0.032	0.031	0.211	1.654
RMS	HOC	TB	0.12	1.082	0.596	0.572	0.256	1.356
RMS	HOC	TB2	0.052	1.034	0.722	0.694	0.337	0.962
RMS	**HOC**	**PT**	**0.025**	**0.083**	**0.02**	**0.019**	**0.045**	**4.497**
RMS	**HOC**	**FCU**	**0.031**	**0.215**	**0.056**	**0.054**	**0.026**	**5.635**
RMS	**HOC**	**ECU**	**0.019**	**0.15**	**0.035**	**0.033**	**0.012**	**7.395**
RMS	Ball	BB	0.085	0.14	0.035	0.031	0.252	1.371
RMS	Ball	TB	0.382	0.477	0.084	0.082	0.425	0.655

RMS	Ball	TB2	0.225	1.073	0.636	0.614	0.346	0.92
RMS	Ball	PT	0.085	0.14	0.035	0.031	0.252	1.371
RMS	**Ball**	**FCU**	**0.051**	**0.135**	**0.026**	**0.025**	**0.03**	**5.281**
RMS	Ball	ECU	0.085	0.14	0.035	0.031	0.252	1.371

Table C.3 ARV statistical analysis between patients and healthy individuals in 6 motions

Metric	Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
ARV	EFE	BB	-0.017	0.02	0.068	0.068	0.705	0.147
ARV	EFE	TB	0.072	0.181	0.087	0.087	0.381	0.791
ARV	EFE	TB2	-0.013	-0.787	0.49	0.49	0.274	1.244
ARV	EFE	PT	-0.004	0.009	0.021	0.021	0.667	0.19
ARV	EFE	FCU	-0.005	0.011	0.017	0.017	0.527	0.411
ARV	EFE	ECU	-0.004	-0.011	0.004	0.004	0.24	1.44
ARV	PS	BB	0.021	0.009	0.026	0.027	0.764	0.092
ARV	PS	TB	-0.051	0.047	0.066	0.07	0.321	1.02
ARV	PS	TB2	0.001	0.044	0.02	0.022	0.155	2.139
ARV	PS	PT	0.003	0.037	0.017	0.018	0.168	2.005
ARV	PS	FCU	-0.008	0.003	0.009	0.01	0.414	0.688
ARV	**PS**	**ECU**	**-0.005**	**-0.036**	**0.006**	**0.006**	**0.001**	**12.545**
ARV	WFE	BB	0.006	-0.011	0.011	0.012	0.317	1.045
ARV	WFE	TB	0.011	0.113	0.059	0.067	0.267	1.296
ARV	WFE	TB2	-0.014	-0.087	0.059	0.066	0.42	0.673
ARV	WFE	PT	-0.002	-0.002	0.005	0.006	0.957	0.003
ARV	WFE	FCU	-0.006	-0.006	0.003	0.004	0.993	0
ARV	**WFE**	**ECU**	**-0.002**	**-0.018**	**0.004**	**0.005**	**0.019**	**6.426**
ARV	URD	BB	0.007	0.042	0.029	0.027	0.383	0.788
ARV	URD	TB	-0.003	-1.149	0.813	0.757	0.312	1.063
ARV	URD	TB2	-0.014	0.87	0.694	0.646	0.36	0.869
ARV	URD	PT	-0.002	0.02	0.014	0.013	0.256	1.348
ARV	URD	FCU	0	0.001	0.01	0.009	0.924	0.009
ARV	URD	ECU	-0.005	0.172	0.14	0.13	0.364	0.853
ARV	HOC	BB	-0.054	-0.054	0.032	0.031	0.987	0
ARV	HOC	TB	0.034	0.519	0.313	0.301	0.276	1.245
ARV	HOC	TB2	0.018	-0.654	0.491	0.472	0.334	0.973
ARV	HOC	PT	-0.007	0.002	0.015	0.015	0.668	0.189
ARV	HOC	FCU	-0.008	-0.023	0.026	0.025	0.663	0.195
ARV	HOC	ECU	-0.006	-0.032	0.021	0.02	0.379	0.804
ARV	Ball	BB	-0.001	-0.016	0.012	0.011	0.345	0.924
ARV	Ball	TB	-0.006	0.079	0.027	0.027	0.036	4.88
ARV	Ball	TB2	-0.013	0.718	0.534	0.516	0.334	0.969

ARV	Ball	PT	-0.006	0.01	0.01	0.009	0.262	1.312
ARV	Ball	FCU	0	-0.041	0.024	0.023	0.223	1.553
ARV	Ball	ECU	-0.001	-0.064	0.029	0.028	0.132	2.406

Table C.2 ZC statistical analysis between patients and healthy individuals in 6 motions

Metric	Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
ZC	**EFE**	**BB**	**278**	**616**	**72.01**	**60.5**	**0.005**	**9.177**
ZC	EFE	TB	332	862	288.9	242.7	0.214	1.623
ZC	EFE	TB2	464	755	177.1	148.8	0.219	1.585
ZC	**EFE**	**PT**	**271**	**849**	**189.9**	**159.5**	**0.028**	**5.428**
ZC	EFE	FCU	591	590	174	146.2	0.994	0
ZC	**EFE**	**ECU**	**303**	**895**	**167.5**	**140.7**	**0.012**	**7.318**
ZC	PS	BB	319	349	49.6	55	0.692	0.16
ZC	PS	TB	425	348	57.9	64.3	0.382	0.789
ZC	PS	TB2	540	336	86.9	96.4	0.127	2.478
ZC	PS	PT	375	554	61	67.6	0.06	3.845
ZC	PS	FCU	744	1434	367	392.7	0.21	1.644
ZC	PS	ECU	481	503	67	71.2	0.822	0.052
ZC	WFE	BB	329	346	66	71.9	0.865	0.029
ZC	WFE	TB	272	310	43	46.9	0.586	0.305
ZC	WFE	TB2	422	564	104	112.91	0.364	0.86
ZC	WFE	PT	525	577	91.9	99.9	0.705	0.147
ZC	WFE	FCU	488	913	269	293	0.296	1.145
ZC	WFE	ECU	749	853	284	309	0.806	0.062
ZC	URD	BB	0.007	0.042	0.029	0.027	0.383	0.788
ZC	URD	TB	-0.003	-1.149	0.813	0.757	0.312	1.063
ZC	URD	TB2	-0.014	0.87	0.694	0.646	0.36	0.869
ZC	URD	PT	-0.002	0.02	0.014	0.013	0.256	1.348
ZC	URD	FCU	N/A	N/A	N/A	N/A	N/A	N/A
ZC	URD	ECU	-0.005	0.172	0.14	0.13	0.364	0.853
ZC	HOC	BB	146	242	43.64	42	0.129	2.479
ZC	HOC	TB	140	350	119	114	0.216	1.616
ZC	HOC	TB2	325	526	104	100	0.179	1.921
ZC	HOC	PT	455	422	70	67	0.74	0.113
ZC	HOC	FCU	461	655	180	174	0.446	0.601
ZC	HOC	ECU	613	513	1856	178	0.7	0.153
ZC	Ball	BB	364	300	38	36.9	0.235	1.473

ZC	Ball	TB	277	569	159	153	0.198	1.745
ZC	Ball	TB2	356	469	59	57	0.178	1.915
ZC	Ball	PT	445	366	73	71	0.443	0.607
ZC	Ball	FCU	845	600	235	227	0.459	0.563
ZC	Ball	ECU	409	468	83.9	81	0.622	0.249

Table C.3 MSA statistical analysis between patients and healthy individuals in 6 motions

Metric	Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
MSA	EFE	BB	0.918	0.527	0.249	0.24	0.269	1.28
MSA	EFE	TB	0.429	0.626	0.167	0.161	0.404	0.72
MSA	**EFE**	**TB2**	**0.122**	**0.392**	**0.089**	**0.093**	**0.046**	**4.397**
MSA	EFE	PT	0.269	0.218	0.092	0.078	0.676	0.179
MSA	EFE	FCU	0.558	0.433	0.164	0.171	0.6	0.283
MSA	EFE	ECU	0.105	0.448	0.108	0.126	0.054	4.289
MSA	PS	BB	0.495	0.241	0.119	0.127	0.155	2.132
MSA	**PS**	**TB**	**0.154**	**0.416**	**0.083**	**0.086**	**0.037**	**4.838**
MSA	PS	TB2	0.089	0.083	0.015	0.018	0.815	0.056
MSA	PS	PT	0.165	0.326	0.088	0.085	0.2	1.729
MSA	PS	FCU	0.172	0.211	0.057	0.06	0.644	0.219
MSA	PS	ECU	0.175	0.36	0.083	0.086	0.133	2.411
MSA	WFE	BB	0.332	0.251	0.058	0.063	0.356	0.888
MSA	WFE	TB	0.218	0.407	0.102	0.112	0.226	1.56
MSA	WFE	TB2	0.095	0.138	0.036	0.039	0.432	0.653
MSA	WFE	PT	0.158	0.247	0.053	0.056	0.263	1.332
MSA	WFE	FCU	0.319	0.51	0.128	0.141	0.328	1.005
MSA	WFE	ECU	0.245	0.398	0.123	0.128	0.397	1.243
MSA	URD	BB	0.373	0.242	0.055	0.051	0.092	3.058
MSA	URD	TB	0.185	0.433	0.12	0.106	0.135	2.402
MSA	URD	TB2	0.071	0.644	0.471	0.376	0.355	0.907
MSA	URD	PT	0.144	0.18	0.054	0.054	0.65	0.212
MSA	URD	FCU	0.178	0.203	0.055	0.05	0.746	0.108
MSA	URD	ECU	0.263	0.318	0.114	0.124	0.748	0.106
MSA	HOC	BB	0.333	0.222	0.063	0.058	0.211	1.663
MSA	HOC	TB	0.204	0.33	0.114	0.108	0.431	0.649
MSA	HOC	TB2	0.064	0.663	0.486	0.406	0.359	0.895
MSA	HOC	PT	0.131	0.219	0.059	0.064	0.326	1.015
MSA	HOC	FCU	0.265	0.308	0.079	0.076	0.703	0.15
MSA	HOC	ECU	0.115	0.429	0.121	0.116	0.074	3.528
MSA	**Ball**	**BB**	**0.314**	**0.199**	**0.029**	**0.028**	**0.008**	**8.102**

MSA	Ball	TB	0.796	0.63	0.103	0.099	0.254	1.36
MSA	Ball	TB2	0.478	0.715	0.309	0.324	0.603	0.279
MSA	Ball	PT	0.382	0.25	0.124	0.114	0.444	0.606
MSA	Ball	FCU	0.394	0.302	0.087	0.087	0.46	0.564
MSA	Ball	ECU	0.187	0.662	0.269	0.31	0.26	1.346

Table C.4 MNF statistical analysis between patients and healthy individuals in 6 motions

Metric	Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
MNF	EFE	BB	120	94	9.697	8	0.05	4.34
MNF	EFE	TB	148	212	105	87	0.641	0.224
MNF	EFE	TB2	289	200	64	53	0.294	1.161
MNF	EFE	PT	113	257	69	57.8	0.127	2.541
MNF	EFE	FCU	313	284	93	77.9	0.81	0.059
MNF	EFE	ECU	303	484	115	95.7	0.242	1.455
MNF	PS	BB	99	168	30	30	0.118	2.726
MNF	PS	TB	219	277	111	111	0.713	0.141
MNF	PS	TB2	655	597	152	152	0.787	0.075
MNF	PS	PT	272	257	50	50	0.836	0.044
MNF	PS	FCU	677	367	133	133	0.122	2.668
MNF	PS	ECU	412	474	102	102	0.675	0.183
MNF	WFE	BB	99.7	94.2	11.8	11.77	0.756	0.099
MNF	WFE	TB	143	122.3	18.75	19.7	0.447	0.602
MNF	WFE	TB2	359	239.7	126	132	0.52	0.429
MNF	WFE	PT	346	333.2	100	105	0.931	0.008
MNF	WFE	FCU	372.8	429.7	92	96.5	0.674	0.182
MNF	WFE	ECU	341	412.4	81.5	85.4	0.553	0.366
MNF	URD	BB	273.7	146.4	109	257	0.657	0.208
MNF	URD	TB	289.6	166.2	100	235	0.639	0.232
MNF	URD	TB2	591.4	147.1	111	261	0.146	2.452
MNF	URD	PT	353.6	243.6	119	278.7	0.723	0.132
MNF	URD	FCU	773.3	654.7	139	326.1	0.744	0.112
MNF	URD	ECU	458.2	223.3	101	237	0.382	0.829
MNF	HOC	BB	90.5	122.7	9.62	13	0.065	3.952
MNF	HOC	TB	197.7	285.5	102	138	0.616	0.262
MNF	HOC	TB2	373.9	670.6	103.6	140.1	0.109	2.899
MNF	HOC	PT	327.2	244	65.3	88.3	0.46	0.576
MNF	HOC	FCU	420.8	483	101	136.8	0.719	0.135
MNF	HOC	ECU	N/A	N/A	N/A	N/A	N/A	N/A
MNF	Ball	BB	118.2	121	15.8	17.5	0.897	0.017

MNF	Ball	TB	143.9	219	66.7	73.7	0.459	0.574
MNF	Ball	TB2	238.9	179	50.7	56.1	0.439	0.625
MNF	Ball	PT	318	213.2	76.5	85	0.37	0.844
MNF	Ball	FCU	504	435.5	102	112.7	0.658	0.203
MNF	Ball	ECU	423	370.4	108	119.8	0.747	0.108

Table C.5 MDF statistical analysis between patients and healthy individuals in 6 motions

Metric	Motion	Muscle	Mean Healthy	Mean Patients	SE Healthy	SE Patients	p Value	F statistic
MDF	EFE	BB	1097	1197	35.851	45	0.095	3.027
MDF	EFE	TB	1178	1216	44.5	56	0.598	0.286
MDF	EFE	TB2	1187	1089	72.7	92	0.414	0.692
MDF	EFE	PT	1086	1131	41.1	52	0.507	0.453
MDF	EFE	FCU	1108	1274	63.1	79.8	0.116	2.661
MDF	EFE	ECU	1144	1114	47.8	60.4	0.699	0.154
MDF	PS	BB	1090	1180	64.8	64.8	0.34	0.966
MDF	PS	TB	1191	1206	78.5	78.6	0.893	0.019
MDF	PS	TB2	1007	1114	54	54	0.179	1.974
MDF	PS	PT	1145	1232	50.8	50.8	0.243	1.467
MDF	PS	FCU	1231	1199	84.2	84	0.79	0.073
MDF	PS	ECU	N/A	N/A	N/A	N/A	N/A	N/A
MDF	WFE	BB	1054	1184	60	67.1	0.169	2.08
MDF	WFE	TB	1029	1055	81.7	91.3	0.837	0.044
MDF	WFE	TB2	1080	1085	68	76	0.969	0.002
MDF	WFE	PT	1187	1088	50.7	56.7	0.213	1.685
MDF	WFE	FCU	1221	1326	70.7	79.1	0.335	0.987
MDF	WFE	ECU	1171	1250	63.4	71	0.417	0.693
MDF	URD	BB	1233	1020	61.5	123	0.16	2.399
MDF	URD	TB	1145	1365	44.4	88.9	0.057	4.913
MDF	URD	TB2	909	1450	107.1	214.3	0.054	5.091
MDF	URD	PT	1109	1061	70.9	142	0.768	0.093
MDF	URD	FCU	970	923	128.7	257.5	0.876	0.026
MDF	URD	ECU	1019	1019	87.2	174.6	0.999	0
MDF	HOC	BB	1122	1089	49.4	60.5	0.673	0.187
MDF	HOC	TB	1243	1153	65.7	80.5	0.403	0.747
MDF	HOC	TB2	1043	1294	85.7	105	0.086	3.443
MDF	HOC	PT	1186	1203	60.8	74.4	0.855	0.035
MDF	HOC	FCU	1149	1147	82	100	0.986	0

MDF	HOC	ECU	995	1055	107	131	0.732	0.123
MDF	Ball	BB	1117	1183	54.3	63.7	0.439	0.629
MDF	Ball	TB	1137	1129	67.8	79.4	0.936	0.007
MDF	Ball	TB2	1107	1090	57.1	67	0.848	0.038
MDF	Ball	PT	1209	1303	63.7	74.6	0.353	0.911
MDF	Ball	FCU	1139	1031	61.4	72	0.269	1.303
MDF	Ball	ECU	1223	1129	57.9	67.9	0.305	1.12

The following section shows comparisons of the patient population at 0–1 month post injury versus 4+ months post injury.

Table C.6 RMS statistical analysis between early rehab patient group and late stage rehab group individuals in 6 motions

Metric	Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0–1 Month	SE 4+ Months	Sig
RMS	EFE	BB	0.221	0.139	0.165	0.062	0.703
RMS	**EFE**	**TB**	**1.35**	**0.413**	**0.283**	**0.185**	**0.01**
RMS	**EFE**	**TB2**	**5.29**	**0.339**	**1.464**	**0.958**	**0.009**
RMS	EFE	PT	0.139	0.094	0.044	0.029	0.408
RMS	EFE	FCU	0.062	0.133	0.07	0.047	0.418
RMS	EFE	ECU	0.110	0.09	0.07	0.04	0.827
RMS	WFE	BB	0.131	0.086	0.049	0.026	0.429
RMS	**WFE**	**TB**	**0.9**	**0.105**	**0.192**	**0.1022**	**0.002**
RMS	WFE	TB2	0.0826	0.222	0.156	0.08	0.438
RMS	WFE	PT	0.0727	0.0596	0.043	0.023	0.791
RMS	WFE	FCU	0.0209	0.178	0.104	0.055	0.2
RMS	WFE	ECU	0.184	0.127	0.072	0.039	0.489
RMS	PS	BB	0.104	0.083	0.079	0.044	0.809
RMS	**PS**	**TB**	**0.861**	**0.133**	**0.24**	**0.13**	**0.014**
RMS	PS	TB2	0.0717	0.158	0.071	0.041	0.3
RMS	**PS**	**PT**	**0.05**	**0.201**	**0.06**	**0.035**	**0.04**
RMS	PS	FCU	0.015	0.0844	0.048	0.028	0.226
RMS	PS	ECU	0.05	0.108	0.055	0.032	0.395
RMS	URD	BB	0.214	0.083	0.05	0.046	0.071
RMS	**URD**	**TB**	**5.377**	**0.123**	**1.592**	**1.43**	**0.022**
RMS	**URD**	**TB2**	**4.27**	**0.088**	**1.498**	**1.34**	**0.049**
RMS	URD	PT	4.2683	0.088	0.0346	0.0309	0.817
RMS	URD	FCU	0.0912	0.0567	0.035	0.0317	0.475
RMS	URD	ECU	0.7954	0.167	0.241	0.2163	0.065
RMS	**HOC**	**BB**	**0.2533**	**0.0893**	**0.061**	**0.04**	**0.035**
RMS	**HOC**	**TB**	**04.202**	**0.1133**	**0.999**	**0.654**	**0.003**
RMS	**HOC**	**TB2**	**4.263**	**0.076**	**1.311**	**0.858**	**0.015**
RMS	HOC	PT	0.111	0.08	0.041	0.027	0.553

RMS	HOC	FCU	0.157	0.216	0.111	0.072	0.659
RMS	HOC	ECU	0.156	0.195	0.068	0.045	0.638
RMS	Ball	BB	0.159	0.069	0.031	0.031	0.051
RMS	Ball	TB	4.415	0.431	0.193	0.193	0.883
RMS	**Ball**	**TB2**	**4.416**	**0.3878**	**1.244**	**1.244**	**0.031**
RMS	Ball	PT	0.077	0.155	0.049	0.0485	0.268
RMS	**Ball**	**FCU**	**0.335**	**0.0634**	**0.04**	**0.037**	**0.000026**
RMS	**Ball**	**ECU**	**0.023**	**0.435**	**0.128**	**0.1285**	**0.032**

Table C.7 ARV statistical analysis between early rehab patient group and late stage rehab group individuals in 6 motions

Metric	Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0–1 Month	SE 4+ Months	Sig.
ARV	EFE	BB	0.078	-0.0789	0.142	0.100927	0.379
ARV	**EFE**	**TB**	**0.722**	**-0.0175**	**0.152**	**0.106913**	**0.001**
ARV	**EFE**	**TB2**	**-3.421**	**-0.2554**	**0.999**	**0.706369**	**0.016**
ARV	EFE	PT	0.0251	0.0221	0.049	0.033161	0.96
ARV	EFE	FCU	-0.011	-0.008	0.039	0.027701	0.957
ARV	**EFE**	**ECU**	**-0.03**	**-0.004**	**0.009**	**0.006035**	**0.017**
ARV	PS	BB	-0.027	0.0072	0.062	0.043549	0.657
ARV	**PS**	**TB**	**0.387**	**-0.0014**	**0.137**	**0.096527**	**0.029**
ARV	PS	TB2	0.018	0.1019	0.045	0.031690	0.14
ARV	PS	PT	0.027	0.0833	0.037	0.026062	0.225
ARV	PS	FCU	-0.003	0.0142	0.021	0.015090	0.523
ARV	PS	ECU	-0.033	-0.047	0.014	0.009819	0.431
ARV	WFE	BB	0.082	-0.134	0.093	0.066210	0.07
ARV	**WFE**	**TB**	**0.709**	**-0.0225**	**0.16**	**0.112527**	**0.001**
ARV	**WFE**	**TB2**	**-3.459**	**-0.0662**	**1.026**	**0.725293**	**0.012**
ARV	WFE	PT	0.03	0.0121	0.032	0.022694	0.657
ARV	WFE	FCU	-0.01	0.0036	0.052	0.036749	0.836
ARV	WFE	ECU	-0.029	-0.0027	0.028	0.020422	0.456
ARV	URD	BB	0.095	0.01433	0.054	0.048776	0.279
ARV	**URD**	**TB**	**-4.255**	**-0.0303**	**1.363**	**1.218694**	**0.03**
ARV	URD	TB2	3.229	0.042	1.199	1.072292	0.06
ARV	URD	PT	0.038	0.04	0.026	0.022880	0.952
ARV	URD	FCU	-0.025	-0.014	0.015	0.013104	0.567
ARV	**URD**	**ECU**	**0.68**	**-0.0233**	**0.237**	**0.212126**	**0.036**
ARV	**HOC**	**BB**	**-0.13**	**-0.012**	**0.065**	**0.042554**	**0.142**
ARV	**HOC**	**TB**	**2.31**	**-0.024**	**0.493**	**0.322551**	**0.001**
ARV	**HOC**	**TB2**	**-2.8**	**0.0162**	**0.892**	**0.584003**	**0.014**
ARV	HOC	PT	-0.05	0.024	0.03	0.019640	0.059
ARV	HOC	FCU	-0.04	-0.0179	0.0553	0.036223	0.792

ARV	HOC	ECU	-0.012	-0.055	0.0433	0.028350	0.423
ARV	BALL	BB	-0.017	-0.0122	0.0265	0.017362	0.093
ARV	BALL	TB	0.097	0.0567	0.0387	0.059006	0.311
ARV	**BALL**	**TB2**	**1.535**	**0.0139**	**0.768**	**1.172901**	**0.001**
ARV	**BALL**	**PT**	**-0.009**	**0.0594**	**0.0123**	**0.018650**	**0.005**
ARV	**BALL**	**FCU**	**-0.09**	**0.00167**	**0.0324**	**0.049571**	**0.002**
ARV	BALL	ECU	-0.008	-0.1422	0.0401	0.061185	0.22

Table C.8 ZC statistical analysis between early rehab patient group and late stage rehab group individuals in 6 motions

Metric	Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0-1 Month	SE 4+ Months	Sig.
ZC	EFE	BB	788.73	547.5	94	94.05	0.082
ZC	EFE	TB	440.27	592.9	434.8	367.45	0.791
ZC	EFE	TB2	1079.25	565.6	290.3	237.04	0.183
ZC	EFE	PT	876.77	414.4	295.2	249.49	0.242
ZC	EFE	FCU	144.83	577.8	421	243.03	0.382
ZC	EFE	ECU	1074.33	998	277.2	209.51	0.828
ZC	PS	BB	274.67	430	139	74.3	0.333
ZC	PS	TB	332.25	462.1	159.6	85.28	0.479
ZC	**PS**	**TB2**	**864**	**230**	220	117.6	**0.018**
ZC	**PS**	**PT**	**1000.25**	**503**	**196.2**	**104.89**	**0.035**
ZC	PS	FCU	1000.25	2037	1019.8	545.09	0.091
ZC	PS	ECU	415.17	583.3	192	102.9	0.448
ZC	WFE	BB	0.12	0.086	0.07	0.03	0.429
ZC	**WFE**	**TB**	**0.9**	**0.1056**	**0.192**	**0.102**	**0.002**
ZC	WFE	TB2	0.083	0.222	0.155	0.083	0.438
ZC	WFE	PT	0.07	0.056	0.04	0.023	0.791
ZC	WFE	FCU	0.021	0.178	0.1	0.056	0.2
ZC	WFE	ECU	0.18	0.127	0.072	0.038	0.489
ZC	URD	BB	396.33	277.2	83.7	54.82	0.312
ZC	URD	TB	239.28	272.	265.8	174	0.918
ZC	URD	TB2	N/A	N/A	N/A	N/A	N/A
ZC	**URD**	**PT**	**1487.5**	**374.2**	**414.5**	**271**	**0.035**
ZC	URD	FCU	1487.5	374.2	386.8	253.2	0.07
ZC	URD	ECU	1789.06	777.6	631.6	413.4	0.193
ZC	HOC	BB	261.67	257	91.8	60.1	0.966
ZC	HOC	TB	56.78	270.7	196.29	128.5	0.373
ZC	**HOC**	**TB2**	**174.4**	**703.3**	**199.31**	**130.48**	**0.038**

ZC	**HOC**	**PT**	**698.06**	**282.1**	**123.47**	**80.83**	**0.011**
ZC	**HOC**	**FCU**	**1436.89**	**474.6**	**329.12**	**215.46**	**0.024**
ZC	HOC	ECU	692.72	478	390.65	255.74	0.651

Table C.9 MSA statistical analysis between early rehab patient group and late stage rehab group individuals in 6 motions

Metric	Motion	Muscle	Mean 0–1 Month	Mean 4+ Months	SE 0–1 Month	SE 4+ Months	Sig.
MSA	EFE	BB	0.0967	-0.132	0.104	0.08	0.07
MSA	**EFE**	**TB**	**0.6**	**-0.04**	**0.177**	**0.137**	**0.001**
MSA	**EFE**	**TB2**	**-3.427**	**-0.06**	**0.159**	**0.112**	**0.012**
MSA	EFE	PT	0.0433	0.013	0.032	0.022	0.621
MSA	EFE	FCU	-0.01	0.0067	0.052	0.037	0.843
MSA	EFE	ECU	-0.0333	0.003	0.029	0.021	0.447
MSA	PS	BB	0.243	0.167	0.29	0.205	0.82
MSA	PS	TB	0.657	0.26	0.174	0.135	0.111
MSA	PS	TB2	0.0833	0.055	0.03	0.027	0.352
MSA	**PS**	**PT**	**0.1**	**0.693**	**0.163**	**0.115**	**0.035**
MSA	PS	FCU	0.26	0.263	0.217	0.088	0.785
MSA	PS	ECU	0.39	0.467	0.185	0.131	0.785
MSA	WFE	BB	0.180	0.277	0.126	0.082	0.673
MSA	WFE	TB	0.66	0.223	0.196	0.139	0.103
MSA	WFE	TB2	0.087	0.164	0.0627	0.049	0.325
MSA	WFE	PT	0.194	0.298	0.104	0.074	0.336
MSA	WFE	FCU	0.351	1.23	0.306	0.163	0.2
MSA	WFE	ECU	0.199	0.439	0.249	0.163	0.375
MSA	URD	BB	0.265	0.22	0.104	0.085	0.837
MSA	**URD**	**TB**	**0.75**	**0.283**	**0.223**	**0.158**	**0.004**
MSA	URD	TB2	1.473	0.19	0.604	0.54	0.215
MSA	URD	PT	0.14	0.285	0.098	0.098	0.711
MSA	URD	FCU	0.27	0.258	0.105	0.091	0.939
MSA	URD	ECU	0.257	0.55	0.245	0.212	0.53
MSA	HOC	BB	0.183	0.21	0.1293	0.085	0.933
MSA	HOC	TB	NA	NA	NA	NA	NA
MSA	HOC	TB2	1.85	0.156	0.692	0.536	0.081
MSA	HOC	PT	0.147	0.33	0.117	0.091	0.272
MSA	HOC	FCU	0.217	0.642	0.154	0.109	0.301
MSA	HOC	ECU	0.207	0.61	0.222	0.145	0.11
MSA	Ball	BB	0.197	0.18	0.184	0.066	0.828
MSA	BALL	TB	1.13	0.697	0.232	0.232	0.96

MSA	**BALL**	**TB2**	**2.66**	**0.467**	**0.602**	**0.492**	**0.019**
MSA	BALL	PT	0.163	0.613	0.24	0.24	0.213
MSA	BALL	FCU	0.525	0.47	0.23	0.19	0.673
MSA	BALL	ECU	0.117	1.677	0.497	0.497	0.076

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