Design and Validation of a Horizontally Dynamic Armrest

by

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Abstract

Design and Validation of a Horizontally Dynamic Armrest

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University of Guelph, 2012

Joystick operators often experience constant low level upper limb loading when using joysticks which can lead to repetitive strain injuries. It has been hypothesized that these injuries can be reduced by supporting the arm during joystick manipulation. The purpose of this work was to design and validate a horizontally dynamic armrest addition. The armrest design followed the motion of the forearm during side-to-side joystick movements. The design was validated using EMG, motion capture, and a questionnaire. Results indicated that the dynamic armrest successfully reduced anterior deltoid and extensor carpi radialis muscle activation ($p \leq 0.01$). Though not significantly, muscle activity was also reduced in the upper trapezius and flexor carpi radialis. Most joint angles were not significantly altered when comparing the dynamic armrest to a stationary armrest or no armrest (except wrist pronation-supination, $p \leq 0.01$), and most subjects preferred the dynamic armrest overall to a stationary armrest or no armrest ($p \leq 0.05$).
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### Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>RSI</td>
<td>Repetitive strain injury</td>
</tr>
<tr>
<td>BB</td>
<td>Biceps brachii</td>
</tr>
<tr>
<td>TB</td>
<td>Triceps brachii</td>
</tr>
<tr>
<td>AD</td>
<td>Anterior deltoid</td>
</tr>
<tr>
<td>PD</td>
<td>Posterior deltoid</td>
</tr>
<tr>
<td>UT</td>
<td>Upper trapezius</td>
</tr>
<tr>
<td>PM</td>
<td>Pectoralis major</td>
</tr>
<tr>
<td>FCR</td>
<td>Flexor carpi radialis</td>
</tr>
<tr>
<td>ECR</td>
<td>Extensor carpi radialis</td>
</tr>
<tr>
<td>MD</td>
<td>Middle deltoid</td>
</tr>
<tr>
<td>ECU</td>
<td>Extensor carpi ulnaris</td>
</tr>
<tr>
<td>MVC</td>
<td>Maximum voluntary contraction</td>
</tr>
<tr>
<td>RVC</td>
<td>Reference voluntary contraction</td>
</tr>
<tr>
<td>tMVC</td>
<td>Task based MVC</td>
</tr>
<tr>
<td>iEMG</td>
<td>Integrated EMG</td>
</tr>
<tr>
<td>pEMG</td>
<td>Peak EMG</td>
</tr>
<tr>
<td>PAR-Q</td>
<td>Physical activity readiness questionnaire</td>
</tr>
<tr>
<td>Sagittal plane</td>
<td>Plane splitting the body into left and right halves</td>
</tr>
<tr>
<td>Frontal plane</td>
<td>Plane splitting the body into anterior and posterior halves</td>
</tr>
<tr>
<td>Transverse Plane</td>
<td>Plane splitting the body into top and bottom halves</td>
</tr>
<tr>
<td>Anterior</td>
<td>Front of the body</td>
</tr>
<tr>
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<td>Back of the body</td>
</tr>
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<tr>
<td>Abduction</td>
<td>Away from body in frontal plane</td>
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<tr>
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</tr>
<tr>
<td>External rotation</td>
<td>Towards back of the body in transverse plane</td>
</tr>
<tr>
<td>Pronation</td>
<td>Towards body in transverse plane</td>
</tr>
<tr>
<td>Supination</td>
<td>Away from body in transverse plane</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

1.1 Background

Operators of joystick controlled mobile machines often experience repetitive loading on the arm and shoulder musculature. Joystick operators in the forestry industry can make as many as 20,000 joystick movements over a 10 hour work day (Golsse 1989), and operators can be working hand operated controls for up to 95% of their working hours in logging machines (Hansson 1990). These constant repetitive upper limb movements can result in arm and neck pain in operators, and constant static loading of muscles at or above 2% maximum voluntary contraction (MVC) for long periods of time (Axelsson & Pontén 1990; Attebrant et al. 1997; Nakata et al. 1993; Gellerstedt 1997). Constant low level loading such as this may lead to the development of repetitive strain injuries (Jonsson 1978). It has been hypothesized that this constant low level muscle activation is a result of the upper arm and shoulder musculature stabilizing the arm during joystick operation (Hansson 1990; Oliver et al. 2012). In attempts to reduce this constant muscle activation some studies have investigated the performance and design of arm supports.

Stationary armrests have been shown to decrease muscle loading in some cases, and increase loading in others (Schüldt et al. 1987; Westgaard & Aarás 1985; Murphy & Oliver 2011; Lindbeck 1982; Hansson 1990). It has been hypothesized that stationary armrests may be inadequate because they support the arm fully when in neutral joystick position, but provide too little support in forward, left, and right joystick positions, and too much support in the backward joystick position (Oliver et al. 2012). Some researchers have tried to remedy this by developing dynamic armrests that move with the forearm during workplace tasks.

Attebrant et al. (1997) developed a dynamic armrest design that translated in the fore-aft direction. The upper trapezius muscle loading was decreased when using the translating armrest in comparison to a fixed armrest. In another study, the motion path the arm followed during fore-aft joystick manipulation with no armrest was investigated. This natural motion path was used to develop a dynamic armrest that accounted for translation in the fore-aft direction, as well as the upward movement of the elbow during forward joystick movements, and the downward movement of the elbow during backward joystick movements (Murphy & Oliver 2008).
Validation of this armrest showed reductions in shoulder and neck muscle activity when compared to a stationary armrest and no armrest (Murphy & Oliver 2011).

1.2 Motivation
Although dynamic armrests have been successful in the past, designs have been restricted to the fore-aft directions. A dynamic armrest designed to follow the forearm motion during side-to-side joystick manipulation may reduce the upper limb muscle activation during these movements. If the design were successful, it could be incorporated into the current fore-aft dynamic armrest design so that the forearm of joystick operators could be supported for all joystick movements. This could further lower the constant muscle activation experienced by joystick operators, which could help to reduce the incidence of repetitive strain injuries amongst operators.

1.3 Objectives
The goal of this study was to reduce muscle activation during side-to-side joystick movements by fully supporting the arm for the duration of these movements, which could help to reduce the risk of developing a repetitive strain injury. The three objectives of the study were as follows:

1. Determine whether a horizontally dynamic armrest could reduce upper limb muscle activation during side-to-side joystick manipulation.

2. Design an addition to a fore-aft dynamic armrest by that would support the arm for the full range of motion during side-to-side joystick movements.

3. Validate the new dynamic armrest using EMG and motion capture techniques to determine if it successfully reduced activation in the arm and shoulder musculature.

1.4 Thesis Structure
This thesis follows journal format, and the purpose of each chapter is as follows. Chapter 1 provides an introduction to the thesis material and outlines the motivation and objectives of the work. Chapter 2 provides a summary of relevant literature and how it relates to the project. Chapter 3 describes the study determining whether a horizontally dynamic armrest could reduce muscle activation, a study to determine the elbow and wrist range of motion during side-to-side joystick movements, and the armrest design. Chapter 4 describes the armrest validation study to determine whether the new armrest design successfully reduced muscle activation in the upper
limb and shoulder musculature. Finally, Chapter 5 summarizes all findings, and shows contributions to literature, conclusions, and future work.

1.5 References


Chapter 2: Literature Review

2.1 Introduction
Joysticks are often used to operate large mobile machinery in industries such as forestry, construction, and mining. The nature of joystick operation often requires operators to be seated for long periods of time performing repetitive movements of the upper limbs, which can lead to pain in the upper limb, or the development of musculoskeletal disorders and repetitive strain injuries (Hansson 1990; Grevsten & Sjögren 1996; Jonsson 1978).

In many cases, workplace changes are implemented in an attempt to reduce the prevalence of repetitive strain injuries (RSIs) and musculoskeletal injuries. There have been studies that have re-designed both joystick controls and armrests to reduce muscle activity in joystick operators (Attebrant et al. 1997; Asikainen & Harstela 1993; Murphy & Oliver 2008). Joystick interventions have included testing both mini levers and pronated hand levers in comparison with conventional hand levers (Attebrant et al. 1997; Asikainen & Harstela 1993; Hagberg & Lidén 1991; Grevsten & Sjögren 1996). Alternatively, stationary and dynamic armrests have been investigated. Stationary armrests may be incapable of supporting the arm fully during joystick operation, as they provide too little support during forward, left, and right joystick movements and too much support during backward joystick movements (Oliver et al. 2012). Forward and side-to-side joystick movements cause the arm to lift off a stationary support, and during backward movements the armrest impedes the downward movement of the elbow. Dynamic armrests have been designed to support the arm fully during joystick movements (Attebrant et al. 1997; Murphy & Oliver 2008). Current dynamic armrest designs support the arm during fore-aft joystick movements, but a horizontally dynamic armrest design could also support the arm during side-to-side joystick movements.

2.2 Anatomy Related to Joystick Use
Upper limb movement can be described as rotations of the limb about three joints: the shoulder, elbow, and wrist. These movements occur in three planes; the frontal, sagittal, and transverse planes (Figure 2-1). Joint rotations in each plane and their descriptions can be found in Table 2-1.
The shoulder joint is made up of four individual joints which include: the glenohumeral joint, the acromioclavicular joint, the sternoclavicular joint, and the scapulothoracic joint (Agur & Dalley 2009). The glenohumeral joint is a synovial ball and socket joint formed where the glenoid fossa of the scapula meets the head of the humerus, at the glenoid cavity (Figure 2-2). This joint allows the shoulder to articulate in three planes; flexion-extension, abduction-adduction, and internal-external rotation. This joint is lightly constrained allowing for a large range of motion (Agur & Dalley 2009; Tortora 2005). The acromioclavicular joint is a synovial planar joint formed where the clavicle meets the acromion (Figure 2-2). This joint allows the clavicle and acromion to glide with shoulder movement. The sternoclavicular joint is a synovial plane and
pivot joint formed where the clavicle meets the sternum and the cartilage of the first rib. This joint allows movement of the clavicle. These three joints are encapsulated and the capsule is filled with synovial fluid allowing the joint to articulate with little friction of the bones. The scapulothoracic joint is formed by the anterior scapula and the posterior thoracic rib cage. This joint allows movement of the scapula (Agur & Dalley 2009; Tortora 2005).

Figure 2-2: The scapula: anterior view of the bones of the right shoulder (Encyclopædia Britannica 2012a)
The elbow is a synovial hinge joint where the humerus bone (upper arm) meets the forearm bones, the radius and ulna (Figure 2-3). The elbow consists of three joints. The humeroradial and humeroulnar joints where the humerus articulates with the radius and ulna, and the proximal radioulnar joint where the radius and ulna meet. The humeroulnar and humeroradial joints form a hinge joint, allowing the elbow to articulate in one plane, flexion and extension. The proximal radioulnar joint allows the radius to rotate with respect to the ulna, allowing forearm and hand pronation and supination (Agur & Dalley 2009; Tortora 2005).

![Anterior view of the human elbow](image)

**Figure 2-3:** Anterior view of a human elbow joint (Encyclopædia Britannica 2012b)
The wrist is a synovial joint made up of the radius, ulna, eight carpal bones, and five metacarpal bones (Figure 2-4). The wrist joint includes the radiocarpal, intercarpal, midcarpal, and carpometacarpal joints. The radiocarpal joint is made up of the radius and the three closest carpals, the scaphoid, lunate, and triquetrum. The intercarpal joints are where each carpal bone meets another. The midcarpal joint is where the three proximal carpal bones meet the four distal carpal bones. The carpometacarpal joints are where the carpal bones meet the metacarpal bones. These joints allow the wrist to move in two planes: flexion-extension, and radial-ulnar deviation (Agur & Dalley 2009; Tortora 2005).

Figure 2-4: Bones of the wrist and hand (Encyclopædia Britannica 2012c)
2.2.1 Muscles Involved in Upper Limb Movement

Several muscles control the movement of the upper limb about the shoulder, elbow, and wrist joints. Table 2-2 shows the muscles activated for movements of the arm about each joint.

**Table 2-2: Main actions of upper limb muscles (Agur & Dalley 2009; Tortora 2005) (Refer to Figure 2-5 through Figure 2-9 for muscle locations)**

<table>
<thead>
<tr>
<th>Joint</th>
<th>Movement</th>
<th>Primary Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>Adduction</td>
<td>Pectoralis Major, latissimus dorsi, subscapularis, teres major, upper trapezius, coracobrachialis</td>
</tr>
<tr>
<td></td>
<td>Abduction</td>
<td>Medial deltoid, upper trapezius, supraspinatus</td>
</tr>
<tr>
<td></td>
<td>Flexion</td>
<td>Pectoralis major, anterior deltoid, biceps brachii, coracobrachialis</td>
</tr>
<tr>
<td></td>
<td>Extension</td>
<td>Latissimus dorsi, posterior deltoid, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>Internal Rotation</td>
<td>Latissimus dorsi, anterior deltoid, subscapularis, teres major, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>External Rotation</td>
<td>Posterior deltoid, infraspinatus, teres minor</td>
</tr>
<tr>
<td>Elbow</td>
<td>Flexion</td>
<td>Brachialis, pronator teres, brachioradialis</td>
</tr>
<tr>
<td></td>
<td>Extension</td>
<td>Triceps brachii, anconeus</td>
</tr>
<tr>
<td></td>
<td>Forearm Pronation</td>
<td>Pronator teres, pronator quadratus</td>
</tr>
<tr>
<td></td>
<td>Forearm Supination</td>
<td>Biceps brachii, supinator</td>
</tr>
<tr>
<td>Wrist</td>
<td>Flexion</td>
<td>Flexor carpi radialis, palmiris longus, flexi carpi ulnaris</td>
</tr>
<tr>
<td></td>
<td>Extension</td>
<td>Extensor carpi radialis, extensor carpi ulnaris</td>
</tr>
<tr>
<td></td>
<td>Radial Deviation</td>
<td>Flexor carpi radialis, extensor carpi radialis</td>
</tr>
<tr>
<td></td>
<td>Ulnar Deviation</td>
<td>Flexi carpi ulnaris, extensor carpi ulnaris</td>
</tr>
</tbody>
</table>

The following figures show muscles of the upper limb and torso. Figure 2-5 shows muscles of the back, Figure 2-6 shows an anterior (front) view of the shoulder muscles, Figure 2-7 shows an anterior view of the upper arm muscles, Figure 2-8 shows a posterior (back) view of the upper arm muscles, and Figure 2-9 shows the forearm muscles.
Figure 2-5: Muscles of the back (Encyclopædia Britannica 2012d)

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Figure 2-6: Shoulder muscles, anterior view (Encyclopædia Britannica 2012d)

© 2008 Encyclopædia Britannica, Inc.
Figure 2-7: Upper arm muscles (Encyclopædia Britannica 2012d)

Figure 2-8: Muscles of the upper arm posterior view (Encyclopædia Britannica 2012d)
2.2.2 Muscles Involved in Joystick Manipulation

There are several muscles involved in making movements required to manipulate a hydraulic actuation joystick. A study by Oliver et al. (2012) on eight upper limb and shoulder muscles determined which muscles were active during each of four joystick movement directions (forwards, backwards, inwards, and outwards). Each movement was broken into two stages. Stage one included joystick movement from the neutral position to the endpoint in the specified direction, and stage two included the movement of the joystick from the endpoint back to the neutral position. The muscles involved in each stage of movement can be seen in Table 2-3.
Table 2-3: Selected upper limb and shoulder muscles involved in forward, backward, inward and outward joystick movements. Stage 1: joystick movement from the neutral position to the endpoint in the specified direction, Stage 2: joystick movement from the endpoint back to the neutral position (Oliver et al. 2012)

<table>
<thead>
<tr>
<th>Joystick Movement</th>
<th>Stage</th>
<th>Muscles Involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>1</td>
<td>Anterior deltoid, extensor carpi radialis, triceps</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Upper trapezius, posterior deltoid</td>
</tr>
<tr>
<td>Backward</td>
<td>1</td>
<td>Upper trapezius, posterior deltoid, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Variety</td>
</tr>
<tr>
<td>Inward</td>
<td>1</td>
<td>Flexor carpi radialis, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Extensor carpi radialis</td>
</tr>
<tr>
<td>Outward</td>
<td>1</td>
<td>Extensor carpi radialis, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Flexor carpi radialis, pectoralis major</td>
</tr>
</tbody>
</table>

2.3 Joystick Kinematics

The range of motion of a typical hydraulic actuation joystick is approximately 20° in all directions (Hansson 1990; Oliver et al. 2007). Studies that have investigated upper limb angle ranges using a 20° range of motion joystick include a study by Oliver et al. (2007) that investigated the ranges of motion during joystick manipulation in four directions, and Murphy & Oliver (2011a) who investigated the angle ranges for the fore-aft direction only. The results of these studies can be seen in Table 2-4 and Table 2-5. The same type of joystick was used in this study so it was assumed that the resulting operator ranges of motion would be similar to these values.
Table 2-4: Upper limb joint angle ranges of motion during joystick control expressed as mean ± standard deviation (in degrees). Negative values indicate extension, external rotation, adduction, radial deviation, or supination (Murphy & Oliver 2007)

<table>
<thead>
<tr>
<th>Joint</th>
<th>Movement</th>
<th>Forward</th>
<th>Backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>Flexion-Extension</td>
<td>8.3±1.4</td>
<td>-8.0±1.5</td>
</tr>
<tr>
<td></td>
<td>Abduction-Adduction</td>
<td>2.1±0.7</td>
<td>2.3±1.2</td>
</tr>
<tr>
<td></td>
<td>Internal-External Rotation</td>
<td>5.5±1.9</td>
<td>-3.4±1.0</td>
</tr>
<tr>
<td>Elbow</td>
<td>Flexion-Extension</td>
<td>-14.6±3.3</td>
<td>8.4±2.0</td>
</tr>
<tr>
<td>Wrist</td>
<td>Flexion-Extension</td>
<td>6.2±2.6</td>
<td>-8.1±3.8</td>
</tr>
<tr>
<td></td>
<td>Radio-Ulnar Deviation</td>
<td>5.5±3.2</td>
<td>-8.0±4.0</td>
</tr>
<tr>
<td></td>
<td>Pronation-Supination</td>
<td>3.7±1.3</td>
<td>-3.7±2.0</td>
</tr>
</tbody>
</table>

Table 2-5: Upper limb joint angle ranges of motion during joystick control expressed as mean ± standard deviation (in degrees) (Oliver et al. 2007)

<table>
<thead>
<tr>
<th>Joint</th>
<th>Movement</th>
<th>Forward</th>
<th>Backward</th>
<th>Inward</th>
<th>Outward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>Flexion-Extension</td>
<td>16.3±4.3</td>
<td>14.0±4.2</td>
<td>4.5±1.8</td>
<td>4.0±2.5</td>
</tr>
<tr>
<td></td>
<td>Abduction-Adduction</td>
<td>4.9±2.3</td>
<td>4.3±1.7</td>
<td>2.8±1.4</td>
<td>3.7±1.9</td>
</tr>
<tr>
<td></td>
<td>Internal-External Rotation</td>
<td>20.1±8.2</td>
<td>30.8±14.6</td>
<td>14.6±3.6</td>
<td>15.0±4.2</td>
</tr>
<tr>
<td>Elbow</td>
<td>Flexion-Extension</td>
<td>23.0±5.6</td>
<td>18.8±3.8</td>
<td>9.6±5.8</td>
<td>6.1±6.8</td>
</tr>
<tr>
<td>Wrist</td>
<td>Flexion-Extension</td>
<td>6.5±4.2</td>
<td>5.0±2.5</td>
<td>9.7±6.7</td>
<td>7.6±4.4</td>
</tr>
<tr>
<td></td>
<td>Radio-Ulnar Deviation</td>
<td>9.1±5.0</td>
<td>12.2±4.5</td>
<td>7.9±9.4</td>
<td>3.6±1.6</td>
</tr>
<tr>
<td></td>
<td>Pronation-Supination</td>
<td>27.0±26.3</td>
<td>43.8±35.2</td>
<td>58.7±28.2</td>
<td>43.4±28.2</td>
</tr>
</tbody>
</table>

2.3.1 Musculoskeletal Disorders

Joystick operators have a high incidence of neck, shoulder, and arm pain and musculoskeletal problems (Hansson 1990; Attebrant et al. 1997; Grevsten and Sjögren 1996; Hagberg and Lidén 1991). Some of these problems have been linked to the repetitive nature of joystick operation (Hagberg & Wegman 1987). There are several musculoskeletal disorders associated with repetitive loading which may lead to pain that many operators report including tendon, muscle, and bursa disorders.

Tendons can become inflamed due to tensile loading under repeated loading conditions (Silverstein et al. 1987). This can cause pain and swelling which can further aggravate the tendon. Muscle disorders due to repetitive loading occur commonly, but the mechanism by
which they occur is unknown. The most widely accepted theory is that increased pressure within the muscle can lead to inflammation and degeneration of the muscle, and can result in muscle pain (Järvholm et al. 1991; Armstrong et al. 1993). The bursa is a fluid filled sac in each of the synovial joints used to decrease friction in joints. Inflammation of the bursa caused by increased friction between the bursa and muscle can also be a result of repetitive loading (Kilbom 2000).

The musculoskeletal disorders described are associated with several workplace physical risk factors which include force, posture, repetition and task duration (Kilbom 2000; Armstrong et al. 1993). There may also be other factors involved including age and past medical history (Kilbom 2000). A summary of some risk factors for musculoskeletal disorders is shown in Table 2-6.

**Table 2-6: Musculoskeletal disorders associated with various physical work factors (NIOSH 1997), where 1 indicates insufficient evidence, 2 indicates some evidence, and 3 indicates strong evidence**

<table>
<thead>
<tr>
<th>Region/Risk Factor</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck &amp; Neck Shoulder</td>
<td></td>
</tr>
<tr>
<td>Repetition</td>
<td>2</td>
</tr>
<tr>
<td>Force</td>
<td>2</td>
</tr>
<tr>
<td>Posture</td>
<td>3</td>
</tr>
<tr>
<td>Vibration</td>
<td>1</td>
</tr>
<tr>
<td>Shoulder</td>
<td></td>
</tr>
<tr>
<td>Repetition</td>
<td>2</td>
</tr>
<tr>
<td>Force</td>
<td>1</td>
</tr>
<tr>
<td>Posture</td>
<td>2</td>
</tr>
<tr>
<td>Vibration</td>
<td>1</td>
</tr>
<tr>
<td>Elbow</td>
<td></td>
</tr>
<tr>
<td>Repetition</td>
<td>1</td>
</tr>
<tr>
<td>Force</td>
<td>2</td>
</tr>
<tr>
<td>Posture</td>
<td>1</td>
</tr>
<tr>
<td>Combination</td>
<td>3</td>
</tr>
</tbody>
</table>

Joystick operators can experience all of the above described risk factors for musculoskeletal disorders. Workplace changes can be used to attempt to reduce the effects of some of these factors, by either implementing new workplace policies or re-designing the controls and tools used by the operators.
2.4 Joystick Ergonomics

Ergonomics is the study of how people interact with their working environments, and it aims to design a workplace that will optimize worker health and productivity. This is important for joystick operators, who often experience pain and musculoskeletal disorders due to the repetitive nature of their task (Hansson 1990; Kilbom 2000). Joystick operators in the forestry industry can make as many as 20,000 joystick movements over a 10 hour work day with one controller (Golsse 1989), and operators can be working hand operated controls for up to 95% of their working hours in logging machines (Hansson 1990).

A literature review conducted by van der Windt et al. (2000) concluded that potential risk factors for arm and shoulder pain include repetition and heavy work load. Many other studies agree that the repetitive nature of joystick operation can be linked with neck and upper limb pain and repetitive strain injuries (Jonsson 1978; Axelsson & Pontén 1990; Hansson 1990; Hagberg & Lidén 1991).

For joystick operators, work load is determined by the resistance of the control lever or joystick used during mobile machine operation. A study investigating upper limb muscle activity at three control lever resistances found that a higher lever resistance increased the muscle loading on the posterior and middle deltoid, but did not significantly increase activity in the upper trapezius or anterior deltoid muscles (Lindbeck 1985, as reported by Hansson 1990). Another study showed that there was no significant difference in muscle activation for stabilizing muscles for different joystick stiffness (such as the posterior deltoid and upper trapezius); however, muscle activation was increased with increased joystick stiffness for prime mover muscles (such as the anterior deltoid, flexor carpi radialis, and extensor carpi radialis) (Oliver et al. 2012).

Although these studies found opposing results for the anterior deltoid and posterior deltoid muscles, both found that the upper trapezius activation was not affected by a change in control stiffness. This indicates that the upper trapezius is likely a stabilizing muscle rather than a prime mover during joystick operation. Several studies have shown that the upper trapezius muscle is active at a low but constant level for all joystick operation tasks, which also supports the assumption that the upper trapezius is a stabilizing muscle for joystick tasks (Hansson 1990; Attebrant et al. 1997; Murphy & Oliver 2007; Oliver et al. 2012). For this reason several studies monitor the upper trapezius activation levels to determine whether workplace modifications are
successful at helping to stabilize the arm. A reduction in upper trapezius muscle activity would indicate that the workplace modification was successful.

Several types of joysticks have been investigated to determine if they could reduce operator muscle activation. A study by Attebrant et al. (1997) compared an ordinary hand lever to a mini lever. A mini lever is a smaller version of a joystick that can be operated by the finger tips resulting in minimal or no arm movement, allowing the arm to rest while the hand operates the lever. It was determined that using a mini-lever decreased the loading in the upper trapezius by 0.7% MVC which preserved or increased productivity in workers when coupled with a translating moveable armrest. The infraspinatus, flexor carpi radialis and extensor carpi ulnaris muscle activations were also reduced when using the mini lever (Attebrant et al. 1997). Similarly, another study determined that using a mini lever could decrease upper trapezius loading (Asikainen & Harstela 1993). The reduction in upper trapezius activity found by these studies is likely because operation of a mini lever requires only the hand and fingers to make movements, allowing the arm to rest so it does not require as much stabilization. The mini lever also reduces the range of motion necessary for hand movement at the wrist joint, which was supported by the muscle activity reduction in the wrist flexor and extensor muscles (Attebrant et al. 1997). However, it was not shown how the forearm muscles that are the prime movers of the fingers were affected by this change.

Mini levers also require increased precision to manipulate because of their smaller size. Attebrant et al. (1997) showed that when comparing a precision task to a simple task, the upper trapezius muscle load doubled. This indicates that although the mini lever successfully reduces the stabilization requirements on the upper trapezius, the increased precision required may negate this success.

Another joystick modification that has been investigated is pronated hand levers. A pronated lever is a joystick that is angled towards the body. This allows the operator’s wrist to be in a more neutral position, but causes abduction of the upper arm and rising of the elbow. The use of pronated joysticks has been linked to increased shoulder pain, neck pain, and sick leave (Hagberg & Lidén 1991; Grevsten & Sjögren 1996), which is likely due to the altered upper arm and elbow positioning.
Both of the joystick modifications listed here, pronated levers and mini levers, were designed to reduce muscle activation of the operator, but they have drawbacks. Alternatively, some researchers have investigated the use of stationary and dynamic armrests to decrease muscle activation.

2.5 Armrests

Armrests are used in joystick controlled mobile machines to support the forearm which could reduce the need for shoulder and neck muscles to stabilize the arm. Studies investigating whether stationary armrests could reduce upper limb and shoulder loading have been equivocal in their results (Schüldt et al. 1987; Westgaard & Aarás 1985; Murphy & Oliver 2011a; Hansson 1990).

In a study investigating simulated assembly tasks, an arm support successfully reduced neck and shoulder muscle activation when compared to no arm support (Schüldt et al. 1987). Another study found that using an armrest (among other ergonomic workplace improvements such as changing from a standing to sitting posture, and workspace height adjustments) significantly reduced muscle activation in the UT (Westgaard & Aarás 1985). In contrast, research by Murphy & Oliver (2011a) showed that muscle activation in the upper trapezius, anterior deltoid, and posterior deltoid increased when using a stationary armrest compared to no armrest during joystick operation for fore-aft movements. Research by Lindbeck (1982, as reported by Hansson 1990) found no significant difference between shoulder and neck muscle activity when comparing a stationary armrest and with no armrest when subjects operated controls in a simulator. Unfortunately, no further details were given on the nature of the simulator or the motions performed. Although the difference was not significant, there was a reduction in upper trapezius muscle activation while subjects used the armrest for all joystick movement directions but backwards; however, deltoid muscle activation increased in half of the subjects with the use of the armrest, especially during backward movement. Muscle activity varied greatly between subjects, and it was concluded that while they had failed to determine whether an armrest was effective at reducing muscle activity, they had determined that controller design and user movement pattern had a great effect on the results.

The conflicting results for stationary armrest studies may be because static armrests are incapable of supporting the arm fully during joystick movements. During forward and side-to-side movements, the arm often lifts off the armrest, so it is not fully supported throughout the
movement range. During backward joystick movements, the armrest impedes the natural downward movement of the elbow, as when no armrest is present, the elbow drops lower than an armrest will allow. This is evidenced in the Lindbeck study (1982, as reported by Hansson 1990) where the backwards movement was the only joystick movement direction for which there was no upper trapezius muscle activity reduction with the armrest addition.

The kinematics of armrest use have also been studied, though not as extensively. One study investigated wrist postures while using a keyboard and no arm support, and a full motion arm support. It was found that the postures, and joint angle ranges were not significantly different between the experimental conditions (Hedge & Powers 1995). Similar results were found in a study comparing a dynamic armrest, stationary armrest, and no armrest during joystick use. There was no significant difference between joint angle ranges between the three armrest conditions (Murphy & Oliver 2011a). The lack of posture alteration while subjects used arm supports in these studies shows that the armrests investigated do not interfere significantly with the subjects’ natural ranges of motion. This could be beneficial to joystick operators as they would not have to alter their learned movements to use a new armrest.

The discrepancies between the muscle activation results for armrest studies is likely dependant on several factors including the type of joystick, armrest, the task being performed, and stature, among others. It has been hypothesized that stationary armrests may be inadequate for joystick use because the armrest is incapable of providing adequate support (Murphy & Oliver 2008). A solution to this problem is the design and use of dynamic armrests that support the arm appropriately for the full range of motion.

2.5.1 Dynamic Armrests
Although stationary armrests cannot support the arm throughout the full range of joystick motion, a dynamic armrest could follow the movements of the forearm during joystick operation. A translating dynamic armrest designed to support the forearm during fore-aft joystick use was studied by Attebrant et al. (1997) and it was determined that this armrest lowered the upper trapezius loading during joystick operation. Although this armrest was successful in reducing upper trapezius muscle loading, it was moveable only in translation in the fore-aft direction and did not follow vertical forearm movement (movement in the z-direction, Figure 2-1). A study by Feng et al. (1997) compared a fixed armrest, a fore-aft dynamic armrest, and a spring loaded arm.
support during four tasks: typing, a simulated assembly task in two different positions, and pipetting. The deltoid and trapezius muscle activations were reduced by both arm supports in comparison to no arm support in all tasks tested. The dynamic armrest was the most successful at reducing loading on these muscles (Feng et al. 1997).

In another investigation, the motion path of the shoulder, elbow and wrist were tracked during joystick manipulation with no armrest. A dynamic armrest was developed to follow this natural motion path, mimicking the forearm pendulation during fore-aft joystick. The natural forearm motion during joystick movement includes the downward movement of the elbow during backward joystick movement and the upward movement of the elbow during forward joystick movement (Murphy & Oliver 2008). In a follow up armrest validation study, the upper trapezius, anterior deltoid, and posterior deltoid muscles showed significantly less activation when using the dynamic armrest as opposed to a static armrest and no armrest. A questionnaire revealed that the subjects felt the dynamic armrest provided more comfort and was more effective than a stationary armrest (Murphy & Oliver 2011a). This armrest differed from that studied by Attebrant et al. (1997) in that it accounted for natural elbow and wrist movement vertically as the arm translates forward and backwards.

The results of these studies show that appropriately designed dynamic armrests have been successful at reducing muscle activation in the upper limb and shoulder musculature, and therefore could help reduce the incidence of RSIs among operators. The success of fore-aft dynamic armrests indicates that a side-to-side dynamic armrest could also result in lowered muscle activation for side-to-side joystick movements. Although no horizontally dynamic armrests have yet been studied, it is hypothesized that such an armrest could also result in muscle activation reductions in muscles responsible for side-to-side joystick movements.

2.6 Electromyography

Electromyography (EMG) is the collection of electrical signals that represent muscle activity, and is used in several ergonomic applications including joystick and armrest studies (Jonsson 1978; Attebrant et al. 1997; Coury et al. 1998). EMG data are collected by placing an electrode on the surface of the skin over a muscle, or inserting a needle electrode directly into a muscle (Webster 1998). A ground electrode is placed in an area where there will be little to no muscle activity, such as over a bony prominence. The ground signal collected is then subtracted from the
EMG signal. The electrical signal picked up is usually very small, so the signal must be amplified before processing (Webster 1998). Before data analysis, an EMG signal is usually normalized as well (Yang & Winter 1984).

The amount of muscle activity during occupational tasks is determined by collecting EMG data, which is usually normalized to reduce variability and allow comparisons between subjects, muscles, and days of data collection (Yang & Winter 1984; Knutson et al. 1994). Normalization is achieved by collecting some type of reference voluntary contraction (RVC) and expressing the data collected as a percentage of this (Yang & Winter 1984; Knutson et al. 1994; Mathiassen et al. 1995). An RVC can be either a maximum voluntary contraction (MVC), where subjects are instructed to flex the muscles indicated to their maximum potential, or sub-maximal, where subjects aim to complete a task requiring a specific amount of force, such as holding a 1 kg weight. Past studies investigating MVCs have been divided in their results. A study by Knutson et al. (1994) showed that MVCs were a reliable method of normalizing data. However, Yang & Winter (1984) showed that sub-maximal RVCs may result in higher reliability than MVCs. This discrepancy could be because some subjects have trouble consistently producing a maximum contraction (Westgaard 1988).

MVCs can be divided into task based and muscle specific contractions. A task based contraction is collected while a subject is in the same anatomical position as during data collection. A muscle specific MVC is collected by performing isolated contractions for each muscle. A literature review conducted by Mathiassen et al. (1995) investigated methods of normalizing upper trapezius EMG data used in ergonomic studies investigating neck and shoulder pain. The conclusion drawn was that collecting an MVC with the subject was in a similar posture to that during the occupational task (a task based MVC, or tMVC) would be useful for studies where the motion of the arm was restricted, such as joystick or armrest studies. For this reason, tMVCs were used for normalization during this joystick study.

Although EMG normalization is a widely accepted data analysis technique, one study indicated that normalization may not be necessary for tasks that require a small percent of the subjects’ maximum strength, such as joystick manipulation. Subjects performed joystick manipulation tasks and data were analysed using three submaximal normalization techniques. tMVC
normalization, muscle specific MVC normalization, and un-normalized EMG results were not significantly different (Murphy & Oliver 2011b).

### 2.7 Conclusions

Based on the available literature, a dynamic armrest design that supports the arm for the full range of motion during side-to-side joystick movements could be a beneficial addition to a fore-aft dynamic armrest. Such a design could help to further reduce the constant low level upper arm and shoulder muscle activation during joystick use that sometimes leads to RSIs.

### 2.8 References


Feng, Y. et al., 1997. Effects of arm support on shoulder and arm muscle activity during sedentary work. Ergonomics, 40(8), pp.834–848.


Chapter 3: Design of a Horizontally Dynamic Armrest

3.1 Introduction

Operators of joystick controlled mobile machines often experience repetitive loading on the arm and shoulder musculature. Several studies have reported constant low level loading at or above 2% maximum voluntary contraction (MVC) in the upper trapezius during light repetitive tasks (Attebrant et al. 1997; Nakata et al. 1993; Gellerstedt 1997). It has been shown that constant low level muscle loading for long periods of time may lead to repetitive strain injuries (Jonsson 1978).

The operation of joystick controlled mobile machines involves making small amplitude repetitive arm movements (Table 3-1) (Oliver et al. 2007). It has been reported that joystick operators in the forestry industry can make as many as 20,000 joystick movements over a 10 hour work day (Golsse 1989), and operators can be working hand operated controls for up to 95% of their working hours in logging machines (Hansson 1990). A study by Axelsson & Pontén (1990) on logging forwarder, processor, and harvester operators showed that neck and upper arm pain could be linked to one sided short repetitive movements. Unfortunately, no further detail was given as to the nature of the controls, other than that they required one-sided, repetitive, short cycle movements of the arms and hands. A literature review conducted by van der Windt et al. (2000) concluded that potential risk factors for arm and shoulder pain include work load, awkward postures, repetitive movements, and duration. The short, repetitive movements made by joystick operators could therefore lead to shoulder, arm, and neck pain.

Table 3-1: Upper limb joint angle ranges of motion during joystick control expressed as mean ± standard deviation (in degrees) (Oliver et al. 2007)

<table>
<thead>
<tr>
<th>Joint</th>
<th>Forward</th>
<th>Backward</th>
<th>Inward</th>
<th>Outward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>Flexion-Extension</td>
<td>16.3±4.3</td>
<td>14.0±4.2</td>
<td>4.5±1.8</td>
</tr>
<tr>
<td></td>
<td>Abduction-Adduction</td>
<td>4.9±2.3</td>
<td>4.3±1.7</td>
<td>2.8±1.4</td>
</tr>
<tr>
<td></td>
<td>Internal-External Rotation</td>
<td>20.1±8.2</td>
<td>30.8±14.6</td>
<td>14.6±3.6</td>
</tr>
<tr>
<td>Elbow</td>
<td>Flexion-Extension</td>
<td>-23.0±5.6</td>
<td>18.8±3.8</td>
<td>-9.6±5.8</td>
</tr>
<tr>
<td>Wrist</td>
<td>Flexion-Extension</td>
<td>6.5±4.2</td>
<td>5.0±2.5</td>
<td>9.7±6.7</td>
</tr>
<tr>
<td></td>
<td>Radio-Ulnar Deviation</td>
<td>9.1±5.0</td>
<td>12.2±4.5</td>
<td>7.9±9.4</td>
</tr>
<tr>
<td></td>
<td>Pronation-Supination</td>
<td>27.0±26.3</td>
<td>43.8±35.2</td>
<td>58.7±28.2</td>
</tr>
</tbody>
</table>
There are several muscles involved in making the repetitive movements necessary for joystick control. Oliver et al. (2012) investigated the effects of joystick stiffness and speed on eight upper limb and shoulder muscles. The primary muscles involved in each direction of joystick movement can be seen in Table 3-2. It was also determined that each of the joystick movements required a constant low level loading between 2-5% task based MVC for all muscles investigated.

Table 3-2: Muscles involved in four joystick movement directions, stage 1: moving the joystick from neutral to endpoint, stage 2: moving the joystick from the endpoint back to neutral position (Oliver et al. 2012)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>Anterior deltoid, flexor carpi radialis, triceps, triceps</td>
<td>Upper trapezius, posterior deltoid</td>
</tr>
<tr>
<td>Back</td>
<td>Upper trapezius, posterior deltoid, pectoralis major</td>
<td>Variety, at low levels</td>
</tr>
<tr>
<td>In</td>
<td>Flexor carpi radialis, pectoralis major</td>
<td>Extensor carpi radialis</td>
</tr>
<tr>
<td>Out</td>
<td>Extensor carpi radialis, pectoralis major</td>
<td>Flexor carpi radialis, pectoralis major</td>
</tr>
</tbody>
</table>

It has been hypothesized that the constant low level loading on muscles during joystick manipulation could lead to RSIs (Jonsson 1978) and other musculoskeletal problems (Hansson 1990; Grevsten & Sjögren 1996). To reduce the loading on the upper limb and possibly the prevalence of musculoskeletal injury in large mobile machine operators, researchers have investigated joystick designs. Lindbeck (1985, as reported by Hansson 1990) investigated the effects of using control levers with three resistance ranges on muscle activation in four shoulder and neck muscles, the upper trapezius (UT), anterior deltoid (AD), middle deltoid (MD), and posterior deltoid (PD). It was determined that changes in joystick resistance affected the PD and MD muscles the most, and had a smaller effect on the UT and AD. However, a similar study showed that joystick stiffness had no effect on the PD and UT, and did have an effect on prime mover muscles including the AD (Oliver et al. 2012). Although the results of these studies are conflicting, both studies show the UT was not affected by joystick stiffness. This is likely because the UT is a stabilizing muscle and not a prime mover during joystick control. Altering
Joystick stiffness is one way to reduce muscle activation, but alternative joystick designs have also been investigated.

Both pronated joysticks and mini levers have been investigated as alternatives to conventional joysticks. The use of pronated joysticks has been linked to increased shoulder pain, neck pain, and sick leave (Hagberg & Lidén 1991; Grevsten & Sjögren 1996). Using a forestry machine simulator, Asikainen & Harstela (1993) compared muscle activity when using mini levers with conventional control levers. Trapezius muscle activity was reduced while using the smaller lever, which was likely a result of the smaller range of motion required by the operator. It was also found that after forestry machine operators adopted the mini lever there were fewer instances of work related shoulder and neck pain. However, in another study the UT activation increased when operators performed a precision task in comparison to a simple task (Attebrant et al. 1997). So although using a mini lever can reduce the stabilization requirements on the UT, it can also increase activation due to precision requirements. As an alternative to control re-designs, some researchers have chosen to investigate the arm supports. It has been hypothesized that the use of an armrest would help to stabilize the arm, and thus reduce the need for UT activation.

Stationary armrests have been investigated to determine if they could reduce muscle activation in operators completing repetitive tasks; however, studies investigating this have been equivocal in their results. One study found that using an armrest (in addition to other ergonomic workplace improvements such as changing from a standing to sitting posture, and workspace height adjustments) reduced muscle activation in the UT (Westgaard & Aarås 1984; Westgaard & Aarås 1985). On the other hand, Lindbeck (1982, as reported by Hansson 1990) found no significant difference between shoulder and neck muscle activity when comparing a stationary armrest with no armrest. Although not significantly different, there was a reduction in UT muscle activation while subjects used the armrest for all joystick movement directions except backwards. This is likely because stationary armrests are designed to support a stationary arm, not arm movement. During joystick manipulation, the arm lifts off a stationary armrest during forward, left, and right movements, and the arm support impedes the downward movement of the elbow during backward joystick movements (Murphy & Oliver 2008).

Though it has been unclear whether stationary armrests are beneficial, it has been hypothesized that dynamic armrests could reduce muscle activity during joystick use. A dynamic armrest
could support the arm throughout the entire range of motion of the arm while performing work related tasks. A study by Attebrant et al. (1997) investigated a fore-aft dynamic armrest in comparison with a stationary armrest. EMG was recorded for the UT, infraspinatus, extensor carpi ulnaris (ECU) and flexor carpi radialis (FCR). Subjects performed a targeting task simulating crane operation, and a tracking task simulating truck driving movement patterns. The UT muscle activation decreased and the FCR and ECU activation increased when using the translating armrest in comparison to a stationary armrest. When surveyed, six out of eight subjects preferred the translating armrest. The increase in the forearm muscle activation (the FCR and ECU) could have been because the armrest translated in only the fore-aft direction, and the tasks performed involved side-to-side joystick movements as well as fore-aft movements.

Recently, another fore-aft dynamic armrest was designed and validated (Murphy & Oliver 2008). The motion of the elbow and wrist was tracked during fore-aft joystick manipulation without an armrest, and a dynamic armrest was designed to mimic this movement. The final design accounted for fore-aft translation as well as the vertical movement of the elbow (the elbow rises during forward joystick movement and lowers during backward joystick movement). The design was tested in a lab setting while subjects performed forward and backward joystick movements. EMG data were collected on the UT, PD and AD muscles (Murphy & Oliver 2011). The muscle activity in all three muscles was reduced when using the dynamic armrest in comparison to a stationary armrest and no armrest. Although this armrest was successful at reducing shoulder muscle activation, it is unclear whether it had an effect on the forearm muscles, which were not investigated. As was determined by Attebrant et al. (1997), the armrest could potentially increase loading on the forearm muscles. The forearm muscles include the FCR and extensor carpi radialis (ECR), which are prime movers during side-to-side joystick movement. The FCR is also active during forwards joystick movement. The purpose of this work was to develop a horizontally dynamic armrest addition to support the arm during side-to-side joystick movements that could be added to the fore-aft dynamic armrest developed by Murphy & Oliver (2011).

The purpose of this work was twofold. The first objective was to determine if a horizontally dynamic addition to the current armrest could reduce muscle activation in the upper limb and shoulder muscles. It was hypothesized that if the forearm was supported during side-to-side
joystick movements as well as fore-aft that the total muscle activation in the arm and shoulder would be reduced. This hypothesis was tested prior to designing the armrest modifications.

The second objective was to further develop the original dynamic armrest by modifying it to support the arm during side-to-side joystick movements which would allow the dynamic armrest to be used to provide support for all joystick movements. The arm trajectory during side-to-side joystick movement with no armrest was determined and was incorporated into the design.

3.2 Dynamic Arm Support Proof of Concept

Prior to designing the change, to determine if a horizontally dynamic armrest could reduce muscle activation, data were collected while a subject performed side-to-side joystick movements with the forearm supported by the experimenter. Ethics approval from the University of Guelph was obtained prior to testing, and the subject provided informed consent after being familiarised with the testing procedures.

3.2.1 Methods

The subject was seated in a laboratory mock-up of an excavator cab with a right-handed joystick (Figure 3-1). The subject was seated at the ergonomically acceptable position with feet flat on the floor and knees bent at 90°. The subject was instructed to sit upright with his back against the back support of the chair. The joystick was adjusted so that when the subject gripped it, the forearm was horizontal while the back was flush with the chair.
3.2.2 EMG Setup
EMG data were collected using a DelSys Bagnoli-8 system, and eight Delsys bipolar surface electrodes (Delsys Inc., Boston MA). The EMG system had a gain of 1000, and a bandwidth of 20-450 Hz, common mode rejection ratio of approximately 92 dB, and input impedance of $>10^{15}$ Ω.

EMG data were collected for five upper arm and shoulder muscles including the biceps, triceps, anterior deltoid, posterior deltoid, and upper trapezius. Five surface EMG electrodes were placed over the belly of each muscle parallel to the muscle fibres as described in Cram et al. (1998) (Figure 3-2). Prior to electrode placement the skin was prepared by shaving any hair in the area,
abrading the skin with fine sandpaper and swabbing with alcohol. The electrodes were also swabbed with alcohol before placement. A ground electrode was placed over the left medial epicondyle. EMG data were sampled at a rate of 1000 Hz.

![Figure 3-2: EMG electrode placement for anterior deltoid (AD), biceps brachii (BB), upper trapezius (UT), posterior deltoid (PD), and triceps brachii (TB)](image)

3.2.3 Test Protocol

The subject performed side-to-side joystick movements while the forearm was supported by the experimenter (Figure 3-3). Each trial consisted of two joystick movements, starting in the neutral joystick position, then moving to the outward endpoint, then immediately to the inward endpoint, and back to neutral (Figure 3-4). The subject was not given any direction as to what speed to perform the movement.
Data were analysed using three custom MatLab® programs (version 7.8, The MathWorks Inc., Natick, MA): emg_main.m, envelope_a.m, and cleave.m (Appendix III). Raw EMG data were band pass filtered between 20 and 400 Hz. The data were then full wave rectified and linear enveloped using a second order low pass 6 Hz Butterworth filter (Winter 2009). EMG files were normalized to the same length to allow for comparison between files. Finally, integrated EMG
(iEMG) and peak EMG (pEMG) values were determined, iEMG represented the total muscle activity for each muscle during the specified joystick movement, and pEMG represented the maximum EMG value within the allotted time period.

### 3.2.4 Results
The linear enveloped EMG is shown in Figure 3-5. pEMG and iEMG data (Table 3-3) showed lower muscle activation while the arm was supported for the biceps brachii (BB), triceps (brachii) TB, AD and PD; and the UT muscle activation remained the same. The peak EMG values decreased while the arm was supported for the B, AD, and UT and slightly increased for the TB, and PD.

![Graph](image)

**Figure 3-5: Linear enveloped EMG of biceps brachii (BB), triceps brachii (TB), anterior deltoid (AD), posterior deltoid (PD), and upper trapezius (UT) for supported and unsupported arm during side-to-side joystick manipulation for one subject**
Table 3-3: Pilot work iEMG and peak EMG Results for supported and unsupported arm during side-to-side joystick movements for one subject

<table>
<thead>
<tr>
<th></th>
<th>iEMG (mV*datapoint)</th>
<th>Biceps</th>
<th>Triceps</th>
<th>Anterior Deltoid</th>
<th>Posterior Deltoid</th>
<th>Upper Trapezius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsupported</td>
<td>62.20</td>
<td>35.33</td>
<td>110.62</td>
<td>31.82</td>
<td>64.13</td>
<td></td>
</tr>
<tr>
<td>Supported</td>
<td>25.00</td>
<td>26.94</td>
<td>52.64</td>
<td>26.72</td>
<td>64.35</td>
<td></td>
</tr>
<tr>
<td>Peak EMG (mV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unsupported</td>
<td>0.024</td>
<td>0.016</td>
<td>0.029</td>
<td>0.008</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Supported</td>
<td>0.014</td>
<td>0.019</td>
<td>0.016</td>
<td>0.009</td>
<td>0.010</td>
<td></td>
</tr>
</tbody>
</table>

The iEMG and pEMG data both show reductions for most muscles when comparing the supported arm to the unsupported arm, but the iEMG seems to show larger reductions. Since the peak and iEMG values decreased or stayed relatively the same in all muscles tested it was assumed that supporting the arm throughout its motion path could lower muscle activation. This indicates that a new armrest design that supports the arm through the full range of motion for side-to-side as well as fore-aft joystick movements could help to reduce the constant low level loading of the muscles.

3.3 Forearm Trajectory Determination

Once it was determined that upper limb muscle activation for side-to-side joystick movements could be reduced while the arm was supported through the full motion path, that motion path was tracked for use in the new armrest design. Ethics approval from the University of Guelph was obtained prior to testing, and the subject provided informed consent after being familiarised with testing procedures.

3.3.1 Methods

Subjects were seated in a laboratory mock-up of an excavator cab with a right-handed joystick (Figure 3-6). Subjects were seated so that their feet were flat on the floor and knees bent at 90°. Subjects were instructed to sit upright with their backs against the back support of the chair. The joystick was adjusted so that when the subject gripped it, the forearm was horizontal while the back was flush with the chair. Three subjects were tested, one female and two male (age, 24±0 years; height, 175±8.7 cm; weight 73±16.2 kg). The subjects had varying statures which represented 50th percentile and 95th percentile male heights (Table 3-4) (NASA 2008).
Figure 3-6: Subject seated in a laboratory mock-up of an excavator cab. Shown with a stationary armrest, for the trajectory determination study, no armrest was used.

Table 3-4: Subject sex, age, height, and weight for the forearm trajectory determination pilot study

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>F</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Age (years)</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>170</td>
<td>175</td>
<td>189</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>55</td>
<td>81</td>
<td>84</td>
</tr>
</tbody>
</table>

3.3.2 Kinematic Data Collection
Data were collected using a six camera Vicon® 460 motion capture system (Vicon Peak, Oxford, UK) while subjects performed side-to-side joystick movements. Five retro-reflective markers were placed on the subject’s right shoulder, elbow, wrist, and middle knuckle, as well as on the joystick to monitor wrist and elbow displacement (Table 3-5, Figure 3-7). Kinematic data were sampled at a rate of 250 Hz.
Table 3-5: Reflective marker names and definitions for wrist range of motion study

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSHO</td>
<td>Right acromio-clavicular joint</td>
</tr>
<tr>
<td>RELB</td>
<td>Lateral epicondyle, approximating elbow joint axis</td>
</tr>
<tr>
<td>RWRI</td>
<td>Right wrist, between RWRA and RWRB</td>
</tr>
<tr>
<td>RFIN</td>
<td>Dorsum of right hand just below head of second metacarpal</td>
</tr>
<tr>
<td>JOY</td>
<td>Top of joystick</td>
</tr>
</tbody>
</table>

Figure 3-7: Reflective marker placement on subject. Refer to Table 3-5 for marker definitions

3.3.3 Test Protocol
Subjects performed side-to-side joystick movements while the forearm was unsupported. Two repetitions were performed of each inward and outward joystick movements. Each trial started with the joystick in the neutral position, then moving to the inward endpoint, then immediately to the outward endpoint, and back to neutral (Figure 3-4). Subjects were instructed to perform the joystick movements at a moderate comfortable speed.

The kinematic data were analyzed using custom Matlab® programs (version 7.8, The MathWorks Inc., Natick, MA): main.m, reorder14.m, ranges.m, and average.m (Appendix III).
The data were cleaved using the x-displacement of the joystick marker (side-to-side movement in the frontal plane) so that the data represented the joystick movement starting and ending in a neutral position. Each trial represented movement from the neutral joystick position to the inwards endpoint, then to the outwards endpoint, and back to neutral. Elbow and wrist marker movement ranges in each direction (x, y, and z, Figure 3-8) were determined for each subject by finding the maximum and minimum x, y, and z displacement values for each marker. The trials were then normalized to the same length, and averaged to show the average movement trajectory.

![Diagram of anatomical reference planes](image)

**Figure 3-8: Anatomical reference planes (Winter 2009)**

### 3.3.4 Results

The displacement ranges of the elbow and wrist markers are shown in Table 3-6. The x axis represents movement to the left or right, and y movement forwards and backwards (see Figure 3-8). The final wrist trajectories in the x-y and x-z planes were then plotted (Figure 3-9, Figure 3-10). One trial for subject 3 was eliminated because too much off axis joystick movement was observed. Off axis movement was defined as any movement that was greater than or equal to 10° away from direct inwards or outwards joystick movement in either the forward or backward directions.
Table 3-6: Wrist and elbow displacement during side-to-side joystick movements, movement axes x, y, and z are shown in Figure 3-8 (n = 3).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Trial</th>
<th>Displacement (mm)</th>
<th>Elbow</th>
<th>Wrist</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>33.7</td>
<td>13.3</td>
<td>23.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15.4</td>
<td>18</td>
<td>11.9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>35.6</td>
<td>28.7</td>
<td>11.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>36.4</td>
<td>13</td>
<td>29.6</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>32.6</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>30.7</td>
<td>18.2</td>
<td>17.9</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>8.7</td>
<td>6.4</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Figure 3-9: Wrist marker displacement in the x-y plane during side-to-side joystick movement, mean and standard deviation for three subjects
The results from the forearm trajectory pilot work showed that the wrist movement during side-to-side joystick manipulation occurred mostly in the x-axis (horizontally, with side-to-side joystick movement). Wrist displacement range in the x-axis was $145.6 \pm 7.3$ mm while the displacement ranges in the y (fore-aft movement) and z (vertical movement) axes were both less than 20mm ($16.5 \pm 6.9$ mm, $19.4 \pm 2.5$ mm respectively, Figure 3-8 shows axes). The data shows that for inwards joystick movement (from neutral to the endpoint), the wrist moved inwards by approximately 75mm, forward by less than 10mm, and downward by approximately 10mm. For outwards joystick movement, the wrist moved outwards by approximately 75mm, backward by approximately 5mm and downward by approximately 10mm.

The elbow displacement ranges were found to be small for the x, y, and z axes ($30.7 \pm 8.7$ mm, $18.3 \pm 6.3$ mm, $17.5 \pm 8.1$ mm). Therefore, the wrist movement in the y and z axes and elbow
movement in all axes were ignored in the side-to-side dynamic armrest design. This resulted in a simpler design that would be easier and more cost effective to manufacture.

3.4 Design Outcome

Following pilot work confirmation, an addition was designed for the original dynamically movable armrest. The addition did not affect the functionality of the original dynamic armrest in the fore-aft direction. It allowed the armrest to rotate in the x-y (transverse) plane about a z-axis pivot point located below the operator’s elbow, thereby supporting side-to-side joystick movements. The dynamic armrest design consisted of the following three parts: the base, inner arm, and outer arm. Technical drawings for each part can be found in Appendix II. An assembly drawing of all three parts can be seen in Figure 3-11.

![Figure 3-11: Horizontally dynamic armrest assembly drawing](image-url)
Finite element analysis was completed on the 3D drawings of the inner arm and the outer arm using SolidWorks® software (SolidWorks 2011, Dassault Systèmes SolidWorks Corp., Massachusetts, USA). Aluminum 6061 was the chosen material because of its high strength and good workability (ASM 2012). The force used was 966.3N which represents the body weight of a 95th percentile male (NASA 2008). Although the arm is the only weight likely to be on the armrest, whole body mass was used so that the armrest would not fail in case of extenuating circumstances, such as the operator leaning heavily on the armrest.

The yield strength of aluminum is 276 MPa, and the maximum von Mises stress the inner arm would experience under a 966.3 N load was 1.3 MPa (Figure 3-12). The FEA showed that the minimum factor of safety of this part was 197. This shows that this part is capable of bearing much larger loads than will likely be seen in the field, so in future iterations of the design, this part could be made smaller, or from a different material if either of these could reduce the cost or increase the effectiveness of the design. Maximum displacement of the part under the applied load was 2.97x10^-4 mm.

![Finite element analysis of inner arm of horizontally dynamic armrest design](image)

**Figure 3-12: Finite element analysis of inner arm of horizontally dynamic armrest design**

The maximum von Mises stress the outer arm would experience under a 966.3 N load was 12.9 MPa (Figure 3-13). Maximum displacement of the part under the applied load was 0.016 mm.
The FEA showed that the factor of safety of this part was 21. The maximum load and displacement experienced by the base were 46.0 kPa and $1.1 \times 10^{-5}$ mm respectively. Since the outer arm had the largest von Mises stress and therefore the smallest factor of safety, this was used as the factor of safety for the entire device, which was 21, indicating that 21 times the maximum load tested (966.3 N) could be applied to the part before it began to yield.

![Finite Element Analysis (FEA) of outer arm of horizontally dynamic armrest design](image.png)

**Figure 3-13: Finite element analysis (FEA) of outer arm of horizontally dynamic armrest design**

Parts were machined from 6061 aluminum, and two bearings were used as shown in Figure 3-11. Three holes were machined into the inner arm to allow the arm to be shortened or lengthened based on the stature of the operator. The hole locations were determined based on 5th, 50th, and 95th percentile male forearm lengths (NASA 2008). A cotter pin could be inserted to hold the arm length in any of the three locations. Aluminum stops were also added to the final design to stop the front bearing from sliding off the base (Figure 3-14). The final product was affixed to the base of the original dynamic armrest as shown in Figure 3-15.
Figure 3-14: Aluminum stops mounted on finished armrest to prevent bearing from sliding off base

Figure 3-15: Final product, horizontally dynamic armrest with fore-aft dynamic armrest mounted above
3.5 Discussion

This design was intended to be a proof of concept for the premise that a horizontally dynamic armrest could decrease muscle loading in upper limb and shoulder muscles during side-to-side joystick manipulation. The two objectives of this chapter were to show whether a horizontally dynamic armrest could reduce muscle loading, and to design a horizontally dynamic armrest according to the natural motion of the forearm during side-to-side joystick movement. The horizontally dynamic armrest design was intended to be an addition to a fore-aft dynamic armrest designed by Murphy & Oliver (2008). This fore-aft dynamic armrest reduced loading in three shoulder and neck muscles when compared to a stationary armrest or no armrest during joystick use (Murphy & Oliver 2011). The device was designed to be used in a laboratory setting, so modifications may be required if it were to be used in the field.

Some studies have shown stationary armrests to be effective at reducing muscle loading during joystick use in the arm and shoulder (Westgaard 1988), and some have found no significant difference between using a stationary armrest and no armrest (Lindbeck 1982, as reported by Hansson 1990). This could be because stationary armrests are incapable of supporting the arm through the full range of motion in joystick use. Fore-aft dynamic armrests have been investigated, and proven to reduce some muscle loading, but a horizontally dynamic armrest has not been designed or tested.

The preliminary EMG results suggested that supporting a subject’s arm while they perform side-to-side joystick movements could reduce the amount of muscle activity (iEMG and pEMG) in the biceps, triceps, anterior deltoid, and posterior deltoid. The activity of the UT muscle was not changed; however, this may be because the UT is a shoulder stabilizing muscle, and the shoulder and elbow are relatively motionless during side-to-side movements (Oliver et al. 2007). The iEMG results showed more pronounced decreases in muscle activity than the pEMG results. This is likely because iEMG is representative of the total EMG for the joystick movement, while the pEMG represents the highest peak during the movement. The iEMG activation decreases represent a lower overall muscle activation for the BB, TB, AD and PD which may be beneficial to joystick operators.

These results are similar to those found by Murphy & Oliver (2011), whose fore-aft dynamic armrest design was shown to decrease loading in the UT, AD, and PD when compared to no
armrest. They are also similar to those found by Attebrant et al. (1997), whose fore-aft translating armrest decreased UT loading. No studies investigating muscle activity for side-to-side joystick movements with different armrest conditions were found.

The muscles that flex and extend the wrist (flexor and extensor carpi radialis) were not investigated in this pilot work because it was assumed that they are used mainly for grip strength, so the activity in these muscles would be relatively similar whether the arm was supported or unsupported. A study by Feng et al. (1997) showed reductions in the deltoid and trapezius muscles when using a dynamic armrest in comparison with a fixed armrest for inclined assembly and pipetting tasks, but found no significant change in the ECR muscle activation. This supports the claim that the ECR activation may not be affected by arm supports.

Once it had been determined that the horizontally dynamic armrest could reduce muscle activity in the arm and shoulder, the motion of the arm during side-to-side joystick movements was investigated to aid in creating a horizontally dynamic armrest design. The wrist and elbow movement of operators during side-to-side joystick movement was recorded and analysed. It was determined that the elbow was relatively stationary (x, y, and z movement ranges all below 32mm) and the wrist had a large horizontal (x-axis) range of motion (approximately 145mm). The wrist also moved in the fore-aft and vertical directions (ranges less than 20mm), however these movements were so small relative to the side-to-side wrist movement that they were ignored in the final design.

The horizontally dynamic armrest design included an arm that rotated about a pivot point located below the operator’s elbow. This allowed the armrest to follow the rotational movement of the forearm about the elbow that was shown by operators during side-to-side joystick movement. An FEA indicated that the armrest design will be able to withstand loads much larger than what would reasonably be placed on an armrest in a field or lab setting. The armrest could easily support the 95th percentile male arm mass (4.8 kg) or the 95th percentile male upper body mass (50.2 kg) (NASA 2008). This results in a safe and robust design that could have applications in any joystick operated vehicle.

Future possible modifications to the armrest that may increase its success include adjusting the motion path of the armrest to incorporate the minimal vertical movement that occurs in the wrist.
during side-to-side joystick movement. If the design were to be used in the field it would also need to be fitted to the specific vehicles it is used in to ensure it is compatible with the controls used and allows the full required range of motion of the arm. If this design is successful, it can be modified accordingly and implemented in large mobile machines that use joysticks in several industries including forestry and construction. The design could also be modified for other applications, and used for any manual task to reduce muscle strain.

3.6 Conclusions

The horizontally dynamic armrest design follows the natural pivoting motion of the forearm during side-to-side joystick manipulation. Pilot work was used to determine that a horizontally dynamic armrest could decrease muscle activation during side-to-side joystick movements. The wrist and elbow trajectories were determined for three subjects (50th and 95th percentile male stature), and the armrest was designed accordingly. The design included telescoping parts and a cotter pin that can be used to extend or shorten the radius of the pivoting motion based on 5th, 50th, and 95th percentile male statures. Validation of the armrest was also completed using 15 subjects in three stature bins, and EMG data of eight upper limb and shoulder muscles. The validation should help to determine whether this armrest design could reduce muscle activation, and possibly the prevalence of musculoskeletal disorders.

3.7 References


Feng, Y. et al., 1997. Effects of arm support on shoulder and arm muscle activity during sedentary work. Ergonomics, 40(8), pp.834–848.


Chapter 4: Dynamic Armrest Validation

4.1 Introduction

Joysticks are used for operation of large mobile machinery in many industries, including forestry, mining and construction. Operators in the forestry industry can be working hand operated controls for up to 95% of their working hours in logging machines (Hansson 1990). It has also been reported that skilled forestry machine operators make as many as 20,000 movements over a 10 hour work day (Golsse 1989). Operators of joystick controlled machines have been known to suffer from neck, shoulder and arm pain (Hansson 1990; Attebrant et al. 1997; Grevsten and Sjögren 1996; Hagberg and Lidén 1991). The musculoskeletal problems reported by joystick operators may be due to the repetitive nature of the task (Hagberg & Wegman 1987; Axelsson & Pontén 1990).

Several studies have reported constant low level loading at or above 2% maximum voluntary contraction (MVC) in the upper trapezius (UT) while operators use joysticks (Attebrant et al. 1997; Nakata et al. 1993; Gellerstedt 1997; Murphy & Oliver 2007). It has been shown that constant low level loading for long periods of time during joystick use may lead to repetitive strain injuries in the shoulder and neck muscles (Jonsson 1978).

Several muscles upper arm and shoulder muscles are activated during joystick control. Table 4-1 lists muscles active during each directional movement of a typical North American joystick.
Table 4-1: Muscles involved in four different joystick movements (Oliver et al. 2012). Stage 1 involves movement from neutral joystick position to the endpoint in the specified direction, stage 2 indicated joystick movement from the endpoint back to neutral position

<table>
<thead>
<tr>
<th>Joystick Movement</th>
<th>Stage</th>
<th>Muscles Involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>1</td>
<td>Anterior deltoid, extensor carpi radialis, triceps</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Upper trapezius, posterior deltoid</td>
</tr>
<tr>
<td>Backward</td>
<td>1</td>
<td>Upper trapezius, posterior deltoid, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Variety</td>
</tr>
<tr>
<td>Inwards</td>
<td>1</td>
<td>Flexor carpi radialis, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Extensor carpi radialis</td>
</tr>
<tr>
<td>Outwards</td>
<td>1</td>
<td>Extensor carpi radialis, pectoralis major</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Flexor carpi radialis, pectoralis major</td>
</tr>
</tbody>
</table>

Mini levers and pronated hand levers have been investigated as alternatives to conventional joysticks. Two studies found that using a mini-lever could decrease the loading in the upper trapezius which preserved or increased productivity in workers when coupled with a moveable armrest (Attebrant et al. 1997; Asikainen & Harstela 1993). Similar results were seen in another study, which also determined that mini levers decreased musculoskeletal symptoms (Hagberg & Lidén 1991). However, mini levers have a higher precision requirement because of the smaller control, and higher precision requirements have been shown to increase muscle activation in the UT (Attebrant et al. 1997). A study on pronated hand levers showed that operators of pronated hand levers had a higher incidence of pain in the elbow and shoulder, and took more sick days due to arm pain (Grevsten & Sjögren 1996). Some researchers have chosen to redesign the armrest rather than the joystick to improve workplace health and performance.

Armrests are used in joystick controlled mobile machines to support the forearm in order to reduce the need for shoulder and neck muscles to stabilize the arm. Studies investigating armrests to determine if they could reduce the activation of muscles while completing workplace
tasks have been divided in their results. Schüldt et al. (1987) showed that the use of an arm support successfully reduced neck and shoulder muscle activation when compared to no arm support. Another study found that using an armrest (among other ergonomic workplace improvements) reduced muscle activation in the UT significantly (Westgaard & Aarås 1985). On the other hand, research by Lindbeck (1982, as reported by Hansson 1990) found no significant difference between shoulder and neck muscle activity when comparing a stationary armrest with no armrest. Although the difference was not significant, there was a reduction in UT muscle activation while subjects used the armrest for all joystick movement directions except backward. It is hypothesized that this is because a stationary armrest impedes the natural downward motion of the elbow during backward joystick movements.

A translating dynamic armrest designed for joystick use was studied by Attebrant et al. (1997) and it was determined that this armrest lowered the upper trapezius loading during joystick operation. This armrest also increased muscle activation in the flexor carpi radialis (FCR) and extensor carpi ulnaris (ECU), some of the muscles responsible for wrist flexion and extension, which are important during side-to-side joystick movements. This armrest may not have been entirely successful because it was moveable only in translation in the fore-aft direction and did not follow forearm pendulation (the up and down movement of the elbow and wrist during joystick control). Another dynamic armrest designed by Murphy & Oliver (2008) translated in the fore-aft and followed forearm pendulation during fore-aft joystick movements. A validation study of this armrest showed that the armrest successfully reduced muscle activation in the UT, anterior deltoid (AD), and posterior deltoid (PD). It is likely that this armrest had greater success because it followed the pendulation as well and the fore-aft translation of the forearm during fore-aft joystick manipulation. Both of these dynamic armrests move in the fore-aft joystick movement direction, but do not follow the arm during side-to-side movements. As indicated by Attebrant et al. (1997), the muscles responsible for side-to-side joystick movements may be negatively impacted by these armrest designs. A horizontally dynamic addition to a fore-aft dynamic armrest that follows the forearm during side-to-side movements could be beneficial in reducing the activation of the wrist flexor and extensor muscles.

The purpose of this study was to determine if the horizontally dynamic addition to the fore-aft dynamic armrest designed by Murphy & Oliver (2008) successfully reduced muscle activation in
selected upper limb and neck muscles. If a reduction in muscle activation was achieved the armrest could give more comfort to large mobile machine operators and potentially reduce the incidence of work related shoulder and neck musculoskeletal injuries.

4.2 Methods
Subjects were seated in a mock-up of an excavator cab in a lab setting, with a North American hydraulic actuation joystick (Figure 4-1). Subjects performed side-to-side joystick movements while using the new horizontally dynamic armrest, a stationary armrest, and no armrest while EMG and motion capture data were collected. The joystick was instrumented with strain gauges which were used to determine when the joystick was in the neutral position, and when it was being moved. Eight ¼ bridge strain gauges were configured into 2 full bridge setups (EA-06-060PB-350, Measurements Group Inc., Micro-Measurements Division, Raleigh, North Carolina; resistance 350±0.2% Ω; gauge factor 2.105±0.5%; transverse sensitivity +0.7±0.2%).

Figure 4-1: Subject setup for validation of a horizontally dynamic armrest, shown with stationary armrest (left) and dynamic armrest (right)
4.2.1 Participants
Fifteen male subjects were recruited for this study from a university population. Prior to testing, approval was obtained from the University of Guelph ethics committee. Subjects were familiarized with testing procedures, then provided informed consent before data collection commenced. Subjects were split into three bins based on their stature. Age, height, and weight data for each subject category can be found in Table 4-2. Subjects had no previous training in operating joysticks in large vehicles. They had no recent history of musculoskeletal disorders or upper limb injuries that could have interfered with testing.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>25.2 ± 2.4</td>
<td>171.2 ± 2.2</td>
</tr>
<tr>
<td>Medium</td>
<td>22.8 ± 1.8</td>
<td>180.8 ± 2.2</td>
</tr>
<tr>
<td>Large</td>
<td>22.8 ± 3.3</td>
<td>189.0 ± 5.5</td>
</tr>
</tbody>
</table>

4.2.2 EMG Setup
A DelSys Bagnoli-8 system (Delsys Inc., Boston MA) was used to collect EMG data to determine whether the muscle activation in several arm and shoulder muscles was reduced when using a horizontally dynamic armrest in comparison with a stationary armrest and no armrest. Eight surface EMG electrodes were attached to each subject’s right arm and shoulder. Electrodes were attached to the following muscles in accordance with Cram et al. (1998). The electrode placement for each muscle can be seen in Figure 4-2.

- Biceps brachii
- Triceps brachii
- Anterior deltid
- Posterior deltid
- Upper trapezius
- Pectoralis major
- Extensor carpi radialis
- Flexor carpi radialis
Figure 4-2: EMG electrode placement for validation of horizontally dynamic armrest for the following muscles: anterior deltoid (AD), pectoralis major (PM), biceps brachii (BB), flexor carpi radialis (FCR), upper trapezius (UT), posterior deltoid (PD), triceps brachii (TB), extensor carpi radialis (ECR)

4.2.3 Motion Capture
The Vicon® 460 Motion capture system (Vicon Peak, Oxford, UK) was calibrated before testing took place. The cameras were set in position to focus on a subject in a seated position, and the axes were aligned as shown in Figure 4-3.
<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>JOY</td>
<td>Top of joystick</td>
</tr>
<tr>
<td>BBX1</td>
<td>Black Base X1</td>
</tr>
<tr>
<td>BBO</td>
<td>Black Base Origin</td>
</tr>
<tr>
<td>BBY1</td>
<td>Black Base Y1</td>
</tr>
<tr>
<td>SPX1</td>
<td>Joystick X1</td>
</tr>
<tr>
<td>SPO</td>
<td>Joystick Origin</td>
</tr>
<tr>
<td>SPY1</td>
<td>Joystick Y1</td>
</tr>
</tbody>
</table>

Figure 4-3: Axis alignment and motion capture markers on the laboratory mock-up of an excavator cab and marker definitions, and lab coordinate system
Markers were placed on the chair base and the subject prior to data collection. The marker descriptions and locations can be seen in Figure 4-3 and Figure 4-4.

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAV</td>
<td>Jugular Notch where the clavicles meet the sternum</td>
</tr>
<tr>
<td>STRN</td>
<td>Xiphoid process of the sternum</td>
</tr>
<tr>
<td>LSHO</td>
<td>Left Acromio-clavicular joint</td>
</tr>
<tr>
<td>RSHO</td>
<td>Right Acromio-clavicular joint</td>
</tr>
<tr>
<td>RUPA</td>
<td>Right upper arm, between shoulder and elbow</td>
</tr>
<tr>
<td>RELB</td>
<td>Lateral epicondyle, approximating elbow joint axis</td>
</tr>
<tr>
<td>RFRA</td>
<td>Right lower arm, between wrist and elbow</td>
</tr>
<tr>
<td>RWRA</td>
<td>Right wrist bar, thumb side</td>
</tr>
<tr>
<td>RWRB</td>
<td>Right wrist bar, pinkie side</td>
</tr>
<tr>
<td>RFIN</td>
<td>Dorsum of right hand just below head of second metacarpal</td>
</tr>
</tbody>
</table>

Figure 4-4: Reflective marker placement on subject and marker definitions.

4.2.4 Test Protocol
Subjects were familiarized with the experimental procedures and asked to provide informed consent before the experiment began. Subjects were asked complete a Physical Activity Readiness Questionnaire (PAR-Q), and their blood pressure was measured. Subjects that were suffering from hand, arm, shoulder, back or neck pain, and subjects with high blood pressure
were excluded from the study. Subjects were also excluded if they were deemed unfit to perform regular physical activity by the PAR-Q results.

Following the placement of the reflective markers and the EMG electrodes, adjustments were made to the chair setup to ensure proper subject posture. It was ensured that the subject’s feet were flat on the floor, knees bent at 90°, and that they were seated all the way back in the chair. The joystick location was changed so that in the neutral joystick position the subject’s forearm was parallel to the floor, and the joystick grip rested comfortably in their hand. Before testing subjects were harnessed to the chair using a Leaf Racewear (Leaf Racewear, London, Ontario) four point harness to ensure that the torso did not move during joystick manipulation. Figure 4-1 shows the subject setup.

4.2.4.1 Task Based MVCs
For EMG processing purposes, task specific reference voluntary contractions (tMVCs) were performed following a similar protocol to Oliver et al. (2012). tMVCs were collected from each subject immediately before the commencement of the experiment trials. For each joystick motion direction (inward and outward, Figure 4-5), subjects were asked to move the joystick to the endpoint in the specified direction and perform a maximal contraction in that position by flexing all right arm and shoulder muscles as hard as possible. Each contraction lasted no longer than 10 seconds, and one minute or more of rest was given between each contraction depending on the subject’s stated fatigue levels. Two tMVC trials were collected for each subject, one for each movement direction. Following each tMVC trial, subjects were asked if they felt they reached their maximum voluntary muscle contraction force and if not the trial was repeated after a minute or more of rest. EMG and motion capture data were collected during these trials.
4.2.4.2 Data Collection

Before testing subjects were given an opportunity to familiarize themselves with the joystick movements they would be performing. Each subject performed six joystick movements for each of three armrest conditions (no armrest, stationary armrest, and dynamic armrest). The six movements consisted of three inwards and three outwards movements (Figure 4-5). Subjects were given the direction of movement verbally directly prior to each trial and were instructed to not use excessive force, but to manipulate the joystick in a way that felt natural to them. For each subject, the order in which the six movements were performed as well as the three armrest conditions used was randomized. When using the dynamic armrest, the forearm of each subject was secured to the armrest using a strap to help the armrest follow the arm motion. Following data collection subjects were asked to fill in a questionnaire about their experience and comfort level using the different armrests (Appendix I: Forms). Subject participation lasted approximately 1.5 hours.
4.2.5 Data Analysis
All data were analyzed using custom Matlab® code, copies of which can be found in Appendix III.

4.2.5.1 EMG Data
EMG data were analyzed using four custom MatLab® programs: main.m, processemg.m, normalize.m, and average.m.

For each subject, the EMG data and the two tMVC trials were loaded using the ‘main.m’ program. Each individual file was bandpass filtered between 20 and 400 Hz, and then normalized using the tMVC of the corresponding movement direction using the functions processemg.m and normalize.m. The EMG data were then passed through a 6 Hz linear envelope (Winter 2009), and each file was cleaved to the joystick movement. This was done by plotting the joystick strain gauge output, and choosing the start and end point of the joystick movement, the starting point was where the strain gauge output changed from a straight line to an increasing slope and the endpoint where it crossed the x-axis, indicating 0 volts (Figure 4-6). All EMG data were then cleaved according to the chosen start and end points.
Figure 4-6: EMG data clipped using joystick strain gauge output using custom Matlab® code, example shown with extensor carpi radialis (ECR) and posterior deltoid (PD) EMG output

The repetitions of each set of conditions (e.g. the three ‘inward’ trials for the dynamic armrest) were normalized to the same length, and averaged using the Matlab® function average.m. Finally, peak EMG was determined by finding the maximum EMG value for each averaged file, and iEMG was calculated for each averaged file using trapezoidal integration. A flowchart of the Matlab® programs can be seen in Figure 4-7.
Figure 4-7: EMG data analysis flowchart
4.2.5.2 Motion Capture Data

Motion capture data were analyzed using four MatLab® programs; maincleave.m, anglesx.m, anglesy.m, anglesz.m, dotproduct.m, and average2.m (Appendix III).

The trials for each subject were loaded using the Matlab® program maincleave.m, and then cleaved using the joystick marker location. The following angles were determined using anglesx.m and dotproduct.m Matlab® functions.

- Shoulder flexion-extension
- Shoulder abduction-adduction
- Shoulder rotation
- Elbow flexion-extension
- Wrist flexion-extension
- Wrist abduction-adduction
- Wrist pronation-supination

The angles were determined by defining vectors to represent each limb, for example, the shoulder and elbow marker were used to create the upper arm vector, and the elbow and wrist markers used to define the forearm vector. The angle between the two vectors (in this case the elbow angle) was then determined using the dot product equation (Figure 4-8, Equation 1). Since this equation is used to determine a two-dimensional angle, angles were found in three planes for each joint (except the elbow, which was approximated as a hinge joint, so only the flexion-extension angle was found).

The joystick angle was determined separately. The neutral position, inward endpoint and outward endpoint were the same for each subject, so the joystick angles were determined once for each subject, and assumed to be similar for all trials. The joystick angle was also determined using the dot product (Equation 1).

Equation 1: Dot product, where \( a \) and \( b \) represent vectors and \( \theta \) the angle between them

\[
\theta = \arccos \left( \frac{a \cdot b}{|a| |b|} \right)
\]
Figure 4-8: Forearm vector, upper arm vector, and angle between them (θ)

Table 4-3: Dot product vector descriptions. Marker locations and descriptions can be found in Figure 4-3 and Figure 4-4.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Pairs of vectors</th>
<th>Markers creating vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joystick side-to-side</td>
<td>1. Joystick base</td>
<td>Joystick base origin (SPO), joystick base center (between joystick base origin (SPO) and y (SPY))</td>
</tr>
<tr>
<td></td>
<td>2. Joystick</td>
<td>Joystick base center (between joystick base origin (SPO) and y (SPY)), Joystick top (JOY)</td>
</tr>
<tr>
<td>Shoulder</td>
<td>1. Clavicle</td>
<td>Clavicle (CLAV), acromion (RSHO)</td>
</tr>
<tr>
<td></td>
<td>2. Upper arm</td>
<td>Acromion (RSHO), elbow (RELB)</td>
</tr>
<tr>
<td>Elbow</td>
<td>1. Upper arm</td>
<td>Acromion (RSHO), elbow (RELB)</td>
</tr>
<tr>
<td></td>
<td>2. Forearm</td>
<td>Elbow (RELB), wrist (between wrist markers A and B (WRA, WRB))</td>
</tr>
<tr>
<td>Wrist</td>
<td>1. Forearm</td>
<td>Elbow (RELB), wrist (between wrist markers A and B (WRA, WRB))</td>
</tr>
<tr>
<td></td>
<td>2. Hand</td>
<td>Wrist (between wrist markers A and B (WRA, WRB)), middle knuckle (RFIN)</td>
</tr>
</tbody>
</table>

Three repetitions of each set of conditions (e.g. all three ‘inward’ trials for the dynamic armrest) were normalized to the same length, and averaged using the function average2.m. Finally,
maximum and minimum angles were determined and output for each averaged file. A flowchart of the Matlab® programs can be seen in Figure 4-9.

Figure 4-9: Motion capture data analysis
4.2.5.3 Statistical Analysis

Statistical analyses were used to determine if the armrest condition affected muscle activation. All statistical analyses were done using Minitab (version 13.32, Minitab, State College, PA, USA). EMG response variables were pEMG and iEMG. 16 ANOVAs were performed for eight muscles and two movement directions (inwards and outwards). 14 ANOVAs were performed on angular output data, one for each of the seven angle ranges calculated, for inwards and outwards directions. The statistical model for EMG and angular data was as follows:

\[ \text{Response variable (iEMG, pEMG, or angle)} = \text{subject (stature)} + \text{stature} + \text{armrest} + \text{error} \]

An ANOVA was performed on the results from the questionnaire given to subjects after they completed data collection. The statistical model was as follows:

\[ \text{Questionnaire response} = \text{subject (stature)} + \text{stature} + \text{armrest} + \text{error} \]

Bonferroni post hoc procedures were performed for comparison of means when significance was found. A significance level of \( p \leq 0.01 \) was used for the EMG and motion capture models because of the large number of ANOVA procedures run. A significance level of \( p \leq 0.05 \) was used for the questionnaire model.

4.3 Results

The following details the EMG, motion capture and questionnaire results obtained from statistical analysis of the gathered data.

4.3.1 EMG

For the inwards movement, upper trapezius, flexor carpi radialis, anterior deltoid, and pectoralis major had the highest activation. For the outwards movement, upper trapezius, pectoralis major, anterior deltoid, and extensor carpi radialis had the largest activations.

The following table shows a summary of the statistically significant results (Table 4-4). Table 4-4 shows that the dynamic armrest increased muscle activation when compared to the stationary armrest or no armrest in some cases for the anterior deltoid and upper trapezius. However, the dynamic armrest significantly reduced pEMG when compared to the stationary armrest for the extensor carpi radialis during outwards movements. The dynamic armrest also reduced iEMG
and pEMG for the FCR in the inwards direction, and iEMG for the extensor carpi radialis (ECR) in the outwards direction in comparison to the stationary armrest, although not significantly.

Table 4-4: EMG ANOVA results for inward and outward directions separately p ≤ 0.01, where no = no armrest, std = stationary armrest, and dyn = dynamic armrest

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Direction</th>
<th>Variable</th>
<th>Main effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior Deltoid</td>
<td>In</td>
<td>iEMG</td>
<td>Std&lt;No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dyn&lt;No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pEMG</td>
<td>Std&lt;No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dyn&lt;No</td>
</tr>
<tr>
<td>Upper Trapezius</td>
<td>In</td>
<td>pEMG</td>
<td>Std&lt;No</td>
</tr>
<tr>
<td>Flexor Carpi Radialis</td>
<td>In</td>
<td>iEMG</td>
<td>No&lt;Std</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No&lt;Dyn</td>
</tr>
<tr>
<td>Extensor Carpi Radialis</td>
<td>Out</td>
<td>pEMG</td>
<td>Dyn&lt;Std</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No&lt;Std</td>
</tr>
</tbody>
</table>

Although it was not significant, the dynamic armrest also reduced the activation of several muscles in comparison to no armrest (Table 4-5).

Table 4-5: Although not significant, the following muscle activations were reduced by the dynamic armrest in comparison to no armrest.

<table>
<thead>
<tr>
<th>iEMG In</th>
<th>iEMG Out</th>
<th>pEMG In</th>
<th>pEMG Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper trapezius</td>
<td>Upper trapezius</td>
<td>Upper trapezius</td>
<td>Upper trapezius</td>
</tr>
<tr>
<td>Extensor carpi radialis</td>
<td>Extensor carpi radialis</td>
<td>Extensor carpi radialis</td>
<td>Extensor carpi radialis</td>
</tr>
<tr>
<td>Biceps brachii</td>
<td>Posterior deltoid</td>
<td>Pectoralis major</td>
<td>Biceps brachii</td>
</tr>
<tr>
<td></td>
<td>Flexor carpi radialis</td>
<td>Triceps brachii</td>
<td>Triceps brachii</td>
</tr>
</tbody>
</table>
The following tables show the iEMG and pEMG results by stature for the dynamic armrest, stationary armrest, and no armrest (Table 4-6 to Table 4-9). The upper trapezius activation for the medium stature group was the largest for most output variables (shown in bold).

**Table 4-6: iEMG mean ± SD (% task based maximal voluntary contraction * seconds) for the inward joystick movement direction**

<table>
<thead>
<tr>
<th>Armrest</th>
<th>Muscle</th>
<th>Stature 1</th>
<th>Stature 2</th>
<th>Stature 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>Biceps</td>
<td>0.83 ± 0.67</td>
<td>3.66 ± 5.93</td>
<td>2.63 ± 2.07</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>0.95 ± 0.35</td>
<td>3.45 ± 6.59</td>
<td>2.60 ± 2.96</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>2.34 ± 3.53</td>
<td>4.07 ± 7.44</td>
<td>4.59 ± 4.00</td>
</tr>
<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>1.88 ± 1.49</td>
<td>3.25 ± 5.68</td>
<td>2.32 ± 1.53</td>
</tr>
<tr>
<td></td>
<td>Pectoralis Major</td>
<td>1.73 ± 1.39</td>
<td>5.99 ± 3.98</td>
<td>4.07 ± 3.06</td>
</tr>
<tr>
<td></td>
<td>Flexor Carpi Radialis</td>
<td>1.88 ± 1.27</td>
<td>5.15 ± 3.79</td>
<td>6.23 ± 3.86</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>2.09 ± 1.26</td>
<td>2.13 ± 1.61</td>
<td>3.05 ± 2.23</td>
</tr>
<tr>
<td>Standard</td>
<td>Biceps</td>
<td>0.83 ± 0.85</td>
<td>3.67 ± 6.53</td>
<td>1.90 ± 1.10</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>0.64 ± 0.49</td>
<td>2.22 ± 3.92</td>
<td>1.64 ± 1.76</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>1.79 ± 2.39</td>
<td>4.30 ± 7.85</td>
<td>3.52 ± 3.33</td>
</tr>
<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>1.12 ± 0.61</td>
<td>2.36 ± 4.04</td>
<td>1.28 ± 1.00</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>4.84 ± 4.65</td>
<td>7.83 ± 6.75</td>
<td>2.74 ± 2.48</td>
</tr>
<tr>
<td></td>
<td>Pectoralis Major</td>
<td>1.60 ± 1.56</td>
<td>7.08 ± 7.47</td>
<td>2.50 ± 2.04</td>
</tr>
<tr>
<td></td>
<td>Flexor Carpi Radialis</td>
<td>1.85 ± 1.04</td>
<td>6.63 ± 3.50</td>
<td>6.52 ± 3.85</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>2.11 ± 1.38</td>
<td>1.77 ± 1.24</td>
<td>1.99 ± 1.55</td>
</tr>
<tr>
<td>None</td>
<td>Biceps</td>
<td>0.77 ± 0.69</td>
<td>3.93 ± 6.96</td>
<td>3.23 ± 3.59</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>1.24 ± 1.32</td>
<td>2.96 ± 5.60</td>
<td>2.72 ± 3.71</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>3.75 ± 3.28</td>
<td>9.65 ± 16.32</td>
<td>6.92 ± 4.57</td>
</tr>
<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>1.63 ± 1.33</td>
<td>2.37 ± 4.14</td>
<td>2.06 ± 1.91</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>9.00 ± 4.46</td>
<td>16.24 ± 8.31</td>
<td>9.56 ± 8.66</td>
</tr>
<tr>
<td></td>
<td>Pectoralis Major</td>
<td>2.58 ± 2.40</td>
<td>7.01 ± 7.04</td>
<td>2.67 ± 2.34</td>
</tr>
<tr>
<td></td>
<td>Flexor Carpi Radialis</td>
<td>1.56 ± 0.53</td>
<td>3.40 ± 1.78</td>
<td>3.10 ± 1.55</td>
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<tr>
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<td>3.51 ± 2.69</td>
<td>1.56 ± 0.78</td>
<td>3.13 ± 3.17</td>
</tr>
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<td>Muscle</td>
<td>Stature 1</td>
<td>Stature 2</td>
<td>Stature 3</td>
</tr>
<tr>
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<td>-------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>Dynamic</td>
<td>Biceps</td>
<td>0.75 ± 0.83</td>
<td>1.22 ± 1.45</td>
<td>1.77 ± 1.29</td>
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<tr>
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<td>Triceps</td>
<td>3.44 ± 2.79</td>
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<td>3.49 ± 1.75</td>
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<tr>
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<td>Anterior Deltoid</td>
<td>2.99 ± 4.24</td>
<td>3.01 ± 4.57</td>
<td>6.03 ± 6.92</td>
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<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>5.34 ± 3.40</td>
<td>4.50 ± 3.88</td>
<td>6.22 ± 4.16</td>
</tr>
<tr>
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<td>7.40 ± 5.82</td>
<td>21.70 ± 29.60</td>
<td>3.45 ± 3.41</td>
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<tr>
<td></td>
<td>Pectoralis Major</td>
<td>6.64 ± 5.71</td>
<td>7.09 ± 10.67</td>
<td>11.13 ± 7.84</td>
</tr>
<tr>
<td></td>
<td>Flexor Carpi Radialis</td>
<td>0.90 ± 0.27</td>
<td>2.22 ± 1.79</td>
<td>3.07 ± 2.02</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>5.74 ± 3.99</td>
<td>7.32 ± 4.43</td>
<td>7.06 ± 4.47</td>
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<td>Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biceps</td>
<td>0.85 ± 1.09</td>
<td>1.48 ± 1.74</td>
<td>2.30 ± 1.59</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>2.43 ± 2.00</td>
<td>3.09 ± 3.40</td>
<td>2.99 ± 1.83</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>2.63 ± 3.59</td>
<td>3.28 ± 4.84</td>
<td>5.22 ± 6.23</td>
</tr>
<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>3.22 ± 1.77</td>
<td>4.39 ± 3.09</td>
<td>4.51 ± 2.60</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>4.85 ± 3.53</td>
<td>7.92 ± 7.22</td>
<td>2.24 ± 1.90</td>
</tr>
<tr>
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<td>Pectoralis Major</td>
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<td>7.00 ± 10.64</td>
<td>10.99 ± 8.07</td>
</tr>
<tr>
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<td>Flexor Carpi Radialis</td>
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<td>2.97 ± 2.10</td>
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</tr>
<tr>
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<td>6.36 ± 5.44</td>
<td>8.97 ± 3.58</td>
<td>9.31 ± 7.16</td>
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<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biceps</td>
<td>1.09 ± 1.35</td>
<td>1.63 ± 1.95</td>
<td>2.53 ± 2.42</td>
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<tr>
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<td>Triceps</td>
<td>3.83 ± 3.96</td>
<td>7.75 ± 13.39</td>
<td>3.13 ± 1.77</td>
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<td>Anterior Deltoid</td>
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<td>8.50 ± 13.52</td>
<td>9.98 ± 10.53</td>
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<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>4.92 ± 3.42</td>
<td>6.47 ± 8.45</td>
<td>6.26 ± 4.94</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>12.14 ± 10.12</td>
<td>17.89 ± 21.68</td>
<td>7.28 ± 6.57</td>
</tr>
<tr>
<td></td>
<td>Pectoralis Major</td>
<td>7.65 ± 5.11</td>
<td>7.73 ± 11.89</td>
<td>10.88 ± 8.09</td>
</tr>
<tr>
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<td>Flexor Carpi Radialis</td>
<td>1.20 ± 0.26</td>
<td>2.68 ± 2.10</td>
<td>4.29 ± 4.18</td>
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<td>Extensor Carpi Radialis</td>
<td>6.07 ± 4.66</td>
<td>6.72 ± 3.65</td>
<td>5.65 ± 3.18</td>
</tr>
</tbody>
</table>
Table 4-8: pEMG mean ± SD (% task based maximal voluntary contraction) for the inward joystick movement direction

<table>
<thead>
<tr>
<th>Armrest</th>
<th>Muscle</th>
<th>Stature 1</th>
<th>Stature 2</th>
<th>Stature 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>Biceps</td>
<td>1.20 ± 1.25</td>
<td>3.22 ± 4.93</td>
<td>3.12 ± 3.60</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>1.26 ± 0.56</td>
<td>3.82 ± 7.37</td>
<td>2.91 ± 3.22</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>1.72 ± 1.52</td>
<td>4.23 ± 6.48</td>
<td>5.99 ± 3.86</td>
</tr>
<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>2.01 ± 0.85</td>
<td>4.15 ± 7.17</td>
<td>3.87 ± 3.05</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>9.82 ± 8.97</td>
<td><strong>17.04 ± 20.05</strong></td>
<td>6.91 ± 6.50</td>
</tr>
<tr>
<td></td>
<td>Pectoralis Major</td>
<td>2.34 ± 1.62</td>
<td>7.28 ± 4.88</td>
<td>7.04 ± 6.51</td>
</tr>
<tr>
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<td>Flexor Carpi Radialis</td>
<td>3.55 ± 3.46</td>
<td>7.70 ± 5.11</td>
<td>11.29 ± 6.97</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>3.27 ± 2.03</td>
<td>3.25 ± 3.04</td>
<td>4.49 ± 3.21</td>
</tr>
<tr>
<td>Standard</td>
<td>Biceps</td>
<td>1.09 ± 0.68</td>
<td>2.73 ± 4.26</td>
<td>3.26 ± 2.58</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>0.80 ± 0.53</td>
<td>2.75 ± 5.15</td>
<td>2.07 ± 1.97</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>1.61 ± 1.50</td>
<td>3.58 ± 5.58</td>
<td>4.65 ± 4.26</td>
</tr>
<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>1.46 ± 0.66</td>
<td>3.02 ± 5.37</td>
<td>2.60 ± 2.35</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>6.75 ± 6.43</td>
<td><strong>6.15 ± 4.42</strong></td>
<td>4.86 ± 4.98</td>
</tr>
<tr>
<td></td>
<td>Pectoralis Major</td>
<td>1.89 ± 1.27</td>
<td>7.37 ± 7.82</td>
<td>5.36 ± 5.67</td>
</tr>
<tr>
<td></td>
<td>Flexor Carpi Radialis</td>
<td>3.50 ± 3.00</td>
<td>11.45 ± 6.39</td>
<td>12.81 ± 5.39</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>3.94 ± 2.22</td>
<td>2.35 ± 1.86</td>
<td>2.87 ± 2.52</td>
</tr>
<tr>
<td>None</td>
<td>Biceps</td>
<td>0.90 ± 0.59</td>
<td>4.16 ± 6.70</td>
<td>4.40 ± 4.66</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>1.48 ± 1.32</td>
<td>3.52 ± 6.50</td>
<td>2.46 ± 2.67</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>7.27 ± 7.50</td>
<td>13.21 ± 22.19</td>
<td>8.94 ± 6.17</td>
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<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>2.15 ± 1.44</td>
<td>2.35 ± 4.02</td>
<td>2.80 ± 3.11</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>14.01 ± 11.43</td>
<td><strong>23.62 ± 17.90</strong></td>
<td>14.58 ± 12.74</td>
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<td>3.49 ± 3.01</td>
<td>9.36 ± 8.46</td>
<td>5.12 ± 4.79</td>
</tr>
<tr>
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<td>Flexor Carpi Radialis</td>
<td>3.44 ± 3.26</td>
<td>6.22 ± 5.03</td>
<td>6.58 ± 4.17</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>5.71 ± 4.38</td>
<td>2.11 ± 1.56</td>
<td>4.04 ± 3.39</td>
</tr>
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Table 4-9: pEMG mean ± SD (% task based maximal voluntary contraction) for the outward joystick movement direction

<table>
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<tr>
<th>Armrest</th>
<th>Muscle</th>
<th>Stature 1</th>
<th>Stature 2</th>
<th>Stature 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Biceps</td>
<td>0.75 ± 0.55</td>
<td>2.18 ± 3.10</td>
<td>2.43 ± 2.51</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>3.69 ± 1.84</td>
<td>4.45 ± 4.85</td>
<td>4.88 ± 2.81</td>
</tr>
<tr>
<td></td>
<td>Anterior Deltoid</td>
<td>1.93 ± 1.90</td>
<td>2.99 ± 4.59</td>
<td>7.82 ± 9.39</td>
</tr>
<tr>
<td></td>
<td>Posterior Deltoid</td>
<td>7.07 ± 6.00</td>
<td>6.44 ± 5.43</td>
<td>10.42 ± 7.24</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>6.13 ± 2.15</td>
<td></td>
<td>25.60 ± 38.70</td>
</tr>
<tr>
<td></td>
<td>Pectoralis Major</td>
<td>7.49 ± 5.46</td>
<td>8.97 ± 12.12</td>
<td>20.67 ± 21.60</td>
</tr>
<tr>
<td></td>
<td>Flexor Carpi Radialis</td>
<td>0.92 ± 0.42</td>
<td>2.32 ± 1.65</td>
<td>5.29 ± 4.46</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>5.83 ± 2.30</td>
<td>7.52 ± 3.91</td>
<td>9.10 ± 3.51</td>
</tr>
<tr>
<td>Dynamic</td>
<td>Biceps</td>
<td>1.08 ± 0.71</td>
<td>2.95 ± 4.18</td>
<td>3.22 ± 3.10</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>3.14 ± 1.21</td>
<td>4.07 ± 4.17</td>
<td>4.32 ± 2.89</td>
</tr>
<tr>
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<td>Anterior Deltoid</td>
<td>3.16 ± 4.47</td>
<td>5.02 ± 7.86</td>
<td>5.58 ± 7.04</td>
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<td>Posterior Deltoid</td>
<td>4.93 ± 2.98</td>
<td>7.34 ± 3.75</td>
<td>8.60 ± 5.81</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>4.49 ± 2.19</td>
<td><strong>7.05 ± 6.26</strong></td>
<td>2.80 ± 2.79</td>
</tr>
<tr>
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<td>Pectoralis Major</td>
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<td>9.58 ± 12.76</td>
<td>18.56 ± 18.91</td>
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<td>Flexor Carpi Radialis</td>
<td>0.93 ± 0.64</td>
<td>4.51 ± 4.14</td>
<td>3.85 ± 2.44</td>
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<td>Extensor Carpi Radialis</td>
<td>6.86 ± 4.40</td>
<td>11.02 ± 5.10</td>
<td>12.84 ± 5.78</td>
</tr>
<tr>
<td>None</td>
<td>Biceps</td>
<td>1.26 ± 0.79</td>
<td>1.65 ± 1.36</td>
<td>3.59 ± 3.12</td>
</tr>
<tr>
<td></td>
<td>Triceps</td>
<td>4.27 ± 2.29</td>
<td>8.16 ± 13.06</td>
<td>4.23 ± 3.02</td>
</tr>
<tr>
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<td>Anterior Deltoid</td>
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<td>8.69 ± 14.18</td>
<td>12.76 ± 15.24</td>
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<td>Posterior Deltoid</td>
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<td>9.06 ± 9.14</td>
<td>9.79 ± 7.00</td>
</tr>
<tr>
<td></td>
<td>Upper Trapezius</td>
<td>12.31 ± 9.15</td>
<td><strong>25.90 ± 42.50</strong></td>
<td>9.55 ± 10.40</td>
</tr>
<tr>
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<td>Pectoralis Major</td>
<td>9.63 ± 4.32</td>
<td>8.53 ± 10.49</td>
<td>13.31 ± 9.76</td>
</tr>
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<td>Flexor Carpi Radialis</td>
<td>2.96 ± 2.88</td>
<td>2.61 ± 2.85</td>
<td>5.43 ± 4.74</td>
</tr>
<tr>
<td></td>
<td>Extensor Carpi Radialis</td>
<td>6.63 ± 2.95</td>
<td>6.80 ± 3.30</td>
<td>7.03 ± 3.12</td>
</tr>
</tbody>
</table>

4.3.2 Motion Capture
The joystick angle ranged from 20-25° for both inwards and outwards movements. Of the seven joint angles calculated, only one showed significant differences between armrest conditions (p≤0.01). Wrist pronation-supination had a significant main effect for stature for the inward joystick direction and armrest had a significant effect for the outwards direction. Subjects in the large stature category had a larger angle range than subjects in the small stature category for the inwards joystick movement. For the outwards joystick movement, the stationary armrest and dynamic armrest resulted in significantly larger wrist pronation-supination angles than no
The full mean and standard deviation results for the in and out directions can be found in Table 4-10 and Table 4-11.

**Table 4-10: Angular range for inwards joystick movements by stature in degrees ± SD.**

Negative values indicate extension, external rotation, adduction, radial deviation, or supination

<table>
<thead>
<tr>
<th>Armrest</th>
<th>Angle</th>
<th>Stature 1</th>
<th>Stature 2</th>
<th>Stature 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>Shoulder Flexion-Extension</td>
<td>14.9 ± 8.1</td>
<td>6.8 ± 2.2</td>
<td>8.0 ± 2.6</td>
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<tr>
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<td>Shoulder Abduction-Adduction</td>
<td>-26.2 ± 23.6</td>
<td>-2.1 ± 0.2</td>
<td>-2.4 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>Shoulder Rotation</td>
<td>23.1 ± 17.7</td>
<td>5.8 ± 1.1</td>
<td>4.8 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>Elbow Flexion-Extension</td>
<td>-23.2 ± 17.3</td>
<td>-12.5 ± 5.8</td>
<td>-8.8 ± 4.1</td>
</tr>
<tr>
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<td>Wrist Flexion-Extension</td>
<td>25.3 ± 45.0</td>
<td>23.3 ± 18.4</td>
<td>16.9 ± 24.3</td>
</tr>
<tr>
<td></td>
<td>Wrist Radial-Ulnar Deviation</td>
<td>-20.1 ± 29.9</td>
<td>-33.0 ± 31.4</td>
<td>-16.1 ± 19.9</td>
</tr>
<tr>
<td></td>
<td>Wrist Pronation-Supination</td>
<td>54.5 ± 26.1</td>
<td>93.0 ± 19.5</td>
<td>128.7 ± 24.0</td>
</tr>
<tr>
<td>Stationary</td>
<td>Shoulder Flexion-Extension</td>
<td>13.9 ± 11.5</td>
<td>5.3 ± 1.3</td>
<td>6.7 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>Shoulder Abduction-Adduction</td>
<td>-16.8 ± 31.5</td>
<td>-1.9 ± 0.3</td>
<td>-1.9 ± 0.9</td>
</tr>
<tr>
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<td>Shoulder Rotation</td>
<td>16.9 ± 22.0</td>
<td>4.0 ± 1.4</td>
<td>5.1 ± 2.2</td>
</tr>
<tr>
<td></td>
<td>Elbow Flexion-Extension</td>
<td>-13.2 ± 3.6</td>
<td>-9.8 ± 5.1</td>
<td>-11.7 ± 5.0</td>
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<td>Wrist Flexion-Extension</td>
<td>5.7 ± 1.7</td>
<td>10.9 ± 7.8</td>
<td>26.8 ± 34.4</td>
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<td></td>
<td>Wrist Radial-Ulnar Deviation</td>
<td>-4.5 ± 1.6</td>
<td>-14.7 ± 21.5</td>
<td>-25.6 ± 28.2</td>
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<tr>
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<td>Wrist Pronation-Supination</td>
<td>72.4 ± 50.4</td>
<td>84.0 ± 40.1</td>
<td>130.3 ± 47.6</td>
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<td>Shoulder Flexion-Extension</td>
<td>6.7 ± 4.8</td>
<td>5.6 ± 2.4</td>
<td>4.4 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>Shoulder Abduction-Adduction</td>
<td>-9.6 ± 15.2</td>
<td>-2.5 ± 1.5</td>
<td>-2.9 ± 0.9</td>
</tr>
<tr>
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<td>Shoulder Rotation</td>
<td>10.1 ± 12.8</td>
<td>5.2 ± 1.2</td>
<td>3.6 ± 1.3</td>
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<td>Elbow Flexion-Extension</td>
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<td>-9.9 ± 2.8</td>
<td>-9.1 ± 3.0</td>
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<td>Wrist Flexion-Extension</td>
<td>35.8 ± 48.5</td>
<td>15.5 ± 25.8</td>
<td>4.7 ± 2.5</td>
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<td>Wrist Radial-Ulnar Deviation</td>
<td>-23.9 ± 14.0</td>
<td>-17.8 ± 13.9</td>
<td>-12.4 ± 9.1</td>
</tr>
<tr>
<td></td>
<td>Wrist Pronation-Supination</td>
<td>55.3 ± 25.4</td>
<td>66.9 ± 43.9</td>
<td>88.4 ± 30.8</td>
</tr>
</tbody>
</table>
Table 4-11: Angular range for outwards joystick movements by stature in degrees ± SD. Negative values indicate extension, external rotation, adduction, radial deviation, or supination

<table>
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<tr>
<th>Armrest</th>
<th>Angle</th>
<th>Stature 1</th>
<th>Stature 2</th>
<th>Stature 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>Shoulder Flexion-Extension</td>
<td>-4.0 ± 3.0</td>
<td>-5.9 ± 3.0</td>
<td>-4.5 ± 2.9</td>
</tr>
<tr>
<td></td>
<td>Shoulder Abduction-Adduction</td>
<td>3.4 ± 2.0</td>
<td>5.2 ± 4.5</td>
<td>2.7 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>Shoulder Rotation</td>
<td>-3.9 ± 1.4</td>
<td>-4.6 ± 2.8</td>
<td>-3.0 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>Wrist Flexion-Extension</td>
<td>-32.8 ± 36.9</td>
<td>-14.1 ± 20.1</td>
<td>-29.1 ± 25.1</td>
</tr>
<tr>
<td></td>
<td>Wrist Radial-Ulnar Deviation</td>
<td>28.6 ± 33.8</td>
<td>16.5 ± 17.7</td>
<td>23.8 ± 23.2</td>
</tr>
<tr>
<td></td>
<td>Wrist Pronation-Supination</td>
<td>-105.7 ± 49.8</td>
<td>-79.8 ± 51.0</td>
<td>-111.4 ± 32.3</td>
</tr>
<tr>
<td>Stationary</td>
<td>Shoulder Flexion-Extension</td>
<td>-6.1 ± 6.3</td>
<td>-4.1 ± 2.0</td>
<td>-2.3 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Shoulder Abduction-Adduction</td>
<td>7.0 ± 12.5</td>
<td>1.9 ± 1.0</td>
<td>1.1 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>Shoulder Rotation</td>
<td>-7.7 ± 11.0</td>
<td>-2.9 ± 1.8</td>
<td>-1.7 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>Elbow Flexion-Extension</td>
<td>-7.6 ± 9.6</td>
<td>-4.8 ± 4.7</td>
<td>-4.5 ± 3.8</td>
</tr>
<tr>
<td></td>
<td>Wrist Flexion-Extension</td>
<td>-27.1 ± 44.4</td>
<td>-10.8 ± 15.4</td>
<td>-6.0 ± 2.6</td>
</tr>
<tr>
<td></td>
<td>Wrist Radial-Ulnar Deviation</td>
<td>15.3 ± 24.2</td>
<td>14.7 ± 12.8</td>
<td>9.4 ± 3.4</td>
</tr>
<tr>
<td></td>
<td>Wrist Pronation-Supination</td>
<td>-91.5 ± 44.4</td>
<td>-82.2 ± 42.6</td>
<td>-134.9 ± 17.0</td>
</tr>
<tr>
<td>None</td>
<td>Shoulder Flexion-Extension</td>
<td>-6.3 ± 6.8</td>
<td>-3.7 ± 1.6</td>
<td>-3.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>Shoulder Abduction-Adduction</td>
<td>7.2 ± 6.9</td>
<td>4.4 ± 2.5</td>
<td>3.0 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>Shoulder Rotation</td>
<td>-11.9 ± 19.3</td>
<td>-4.1 ± 1.8</td>
<td>-4.1 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>Elbow Flexion-Extension</td>
<td>-34.0 ± 36.7</td>
<td>-8.8 ± 4.7</td>
<td>-7.2 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>Wrist Flexion-Extension</td>
<td>-82.8 ± 64.5</td>
<td>-10.2 ± 9.6</td>
<td>-5.2 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>Wrist Radial-Ulnar Deviation</td>
<td>57.5 ± 46.9</td>
<td>10.1 ± 3.7</td>
<td>17.8 ± 17.5</td>
</tr>
<tr>
<td></td>
<td>Wrist Pronation-Supination</td>
<td>-87.6 ± 49.9</td>
<td>-44.5 ± 36.8</td>
<td>-49.6 ± 24.6</td>
</tr>
</tbody>
</table>

4.3.3 Questionnaire
Out of the total of 15 subjects, nine preferred the dynamic armrest overall, four preferred the stationary armrest and one preferred no armrest. One subject could not decide between the dynamic and stationary armrest. Although some subjects preferred the stationary armrest, two of them stated that they preferred the dynamic armrest for side-to-side movements. There were no significant differences in question responses between statures.

Subjects were asked to rate the overall effectiveness of the stationary and dynamic armrest, and only one subject rated the stationary armrest more effective than the dynamic. Although the
difference was not significant, the dynamic armrest was rated more effective than the stationary armrest. The scores out of 7 were as follows: stationary armrest, 4.5, dynamic armrest, 5.9.

Subjects were also asked to rate the perceived effort and perceived discomfort of all three armrest conditions. Both of these questions were found to have statistically significant results (p≤0.05). The dynamic armrest required a higher perceived effort than no armrest; however, the means scores out of 7 were 2.9 and 3.6, so it was not a large difference. Similarly, the dynamic armrest was found to have a higher perceived discomfort than no armrest, although it was not significantly greater than the stationary armrest.

4.4 Discussion

Previous studies have investigated dynamic armrests in the fore-aft joystick movement directions (Attebrant et al. 1997; Murphy & Oliver 2008). Attebrant et al. (1997) found that a translational fore-aft dynamic armrest reduced muscle activation in the UT, but increased activation in the FCR and ECU, the wrist flexor and extensor muscles important in side-to-side joystick movements. Murphy & Oliver (2008) found that a fore-aft pendulating armrest reduced UT, PD, and AD muscle activation, but the forearm muscles were not investigated as this armrest was only tested for the fore-aft directions of joystick movement. This study was concerned with validating a horizontally dynamic addition to the pendulating fore-aft dynamic armrest to determine whether it could successfully reduce muscle activation for side-to-side joystick movements.

The FCR and ECR muscles are wrist flexor and extensor muscles respectively, and are two of the most important muscles involved in side-to-side joystick manipulation (Oliver et al. 2012). For this reason, these muscles were deemed the most important in assessing the horizontally dynamic armrest success.

The highest muscle activation for both iEMG and pEMG for the inwards joystick movement occurred in the UT. High activations were also seen in the FCR and the AD. This agrees with past research done by (Oliver et al. 2012), who showed that for the inwards movement, highest activation was observed for the FCR and PM. (Oliver et al. 2012) also indicated that the UT had a constant low level activation of close to 10% tMVC throughout inwards movements. The high activation of these three muscles stands to reason as the UT elevates and stabilizes the shoulder,
FCR flexes the wrist, and AD medially rotates the arm (Agur & Dalley 2009). These are all actions required for inwards joystick movement.

For outwards joystick movement, the highest muscle activation was seen in the UT, PM and ECR. Oliver et al. (2012) showed highest activation for the outwards joystick movement for the ECR and PM, and indicated that the UT had a constant low level activation of close to 5% tMVC throughout outwards movements. This makes sense as the upper trapezius raises the shoulder, pectoralis major laterally rotates the shoulder, and the extensor carpi radialis extends the wrist, all of which are essential during outwards joystick movement (Agur & Dalley 2009; Oliver et al. 2012).

The success of the dynamic armrest was determined based on whether it reduced muscle activation in the eight arm and shoulder muscles tested, especially for the FCR and ECR muscles in comparison to a stationary armrest and no armrest. Statistically significant differences in EMG output variables between armrest conditions were only seen for four out of the eight muscles tested (the AD, UT, FCR, and ECR).

AD muscle activation while using the dynamic armrest was significantly smaller than for no armrest in all cases. There was no significant difference for the AD between the stationary and dynamic armrests. AD activation is far higher during forwards and backwards joystick manipulation than for side-to-side (Oliver et al. 2012), but the AD does assist in internal rotation of the shoulder, which is required for the inwards joystick movement (Agur & Dalley 2009; Oliver et al. 2012). The dynamic armrest successfully reduced AD activation in comparison to no armrest; however, because it was not significantly different from the stationary armrest therefore, this was only a partial success.

Although it was not significant, the dynamic armrest decreased the activation of the UT in comparison with no armrest in all cases. This indicates that the dynamic armrest was successful in stabilizing the arm during side-to-side movements. The stationary armrest also resulted in a significantly lower UT activation for pEMG in the inwards direction when compared to no armrest. This is similar to the results of some studies that found that the UT activation could be lowered by a stationary armrest (Westgaard & Aarås 1985; Lindbeck 1985 as reported by Hansson 1990), but is in contrast with (Murphy & Oliver 2011) which observed increased UT
activation during stationary armrest use. However, the Murphy & Oliver (2011) study only monitored forward and backward joystick motion, whereas the current study investigated side-to-side movements. It is possible that a stationary armrest may reduce UT activation for some joystick movements and increase it for others, which may be one reason for the equivocal study results.

FCR muscle activation for the dynamic armrest was only significantly higher than for no armrest in one case (iEMG in the inwards direction). For the inwards direction, the FCR activation was smaller for the dynamic armrest in comparison to the stationary armrest although not significantly (for iEMG and pEMG). The FCR is the main muscle involved in wrist flexion and inwards joystick movement (Agur & Dalley 2009; Oliver et al. 2012).

For the ECR in the outwards direction, pEMG was significantly lower for the dynamic armrest than the stationary armrest. iEMG was also smaller for the dynamic armrest than the stationary armrest, although not by a significant amount. The ECR is the main muscle involved in wrist extension, and outwards joystick movement (Agur & Dalley 2009; Oliver et al. 2012). Therefore, the dynamic armrest successfully reduced the muscle activation required to perform the outwards joystick movement.

The joystick range of motion in this study was 20-25° in each direction, which agrees with past research using similar joysticks, which state the joystick range as approximately 20° (Oliver et al. 2007; Murphy & Oliver 2011), and Oliver et al. (2012) who found an joystick angle range of 22°. The statistical results for the joint angle motion capture data showed that for most angles, there was no difference between stature or armrest condition. This was the expected result, as the dynamic armrest was designed to follow the natural movement of the forearm during joystick movement. The natural forearm movement was determined by studying a subject’s arm movement with no armrest (Section 3.2: Dynamic Arm Support ). However, there was one angle for which significant differences were found. For inwards joystick movements, wrist pronation-supination ranges were larger for large stature subjects when compared to small stature subjects. Wrist pronation-supination ranges were also larger for the dynamic armrest and the stationary armrest when compared to no armrest. Subjects of a larger stature may have a larger wrist pronation-supination because of the larger size of their limbs. It is common for mobile machine operators to use stationary armrests in the field so the fact that the wrist pronation-supination for
the dynamic armrest is not significantly different from that of the stationary armrest shows that operators would not be changing their normal motion path of wrist pronation-supination.

For both inwards and outwards movements, small shoulder angle ranges were seen, which is likely due to the fact that the shoulder is relatively stationary during side-to-side joystick movements, as the elbow does not move much vertically (Oliver et al. 2007). The elbow has a slightly larger angle range, as it is the joint about which the forearm rotates to perform the side-to-side joystick movements. Wrist flexion-extension and radial-ulnar deviation ranges were again slightly larger than the elbow ranges. For side-to-side joystick movements, the primary muscles involved are the flexor and extensor carpi radialis, which are involved in wrist flexion and extension (Oliver et al. 2012). The elbow, shoulder and wrist angles are similar to those determined in the past literature (Oliver et al. 2007). For all three armrest conditions, the largest angle ranges were seen in the wrist pronation-supinations, which also agrees with past work by Oliver et al. (2007).

Questionnaire results showed that the dynamic armrest was perceived to be significantly more uncomfortable, and to take significantly more effort than no armrest. However, the dynamic armrest was not significantly higher in either category than the stationary armrest. Subjects may have found the armrest uncomfortable because of the lateral distance between the armrest and the chair, some subjects stated that the distance was uncomfortably large. Adding lateral adjustment capability to the armrest may help with this. Another possible reason the armrest was perceived uncomfortable could have been the strap used to secure the subjects’ arm to the armrest. Replacing this with a sleeve may also increase operator comfort because it may allow the armrest to follow the forearm movement more accurately than a strap which secures the forearm to the armrest in one location only. Although it was rated more uncomfortable, the majority of subjects preferred the dynamic armrest, and rated it more effective than the stationary armrest. This indicates that operators in the field would be likely to use the dynamic armrest, as it would not be more uncomfortable than the stationary armrests currently used by many operators.

4.5 Conclusions
Overall the dynamic armrest was successful in reducing the muscle activation of the anterior deltoid and the extensor carpi radialis. Evidence was also seen of muscle activity reductions for the upper trapezius and flexor carpi radialis, but these results were not statistically significant.
Reductions were seen for the prime mover muscles for side-to-side joystick movements (FCR and ECR), although not always significant, which indicates the armrest was a partial success. Using a dynamic armrest did not significantly change upper limb angle ranges when compared to a stationary armrest, and only significantly changed one angle range in the wrist when compared to no armrest. The similar angle ranges indicate operators would not have to alter their natural movement patterns to use the dynamic armrest. Finally, subjects rated the effort and discomfort while using the dynamic armrest similar to that of using a stationary armrest. Subjects preferred the dynamic armrest overall, and rated it the most effective.

The results indicate that implementing a horizontally dynamic armrest may help to reduce complaints of arm and shoulder pain in operators, and the incidence of musculoskeletal disorders.

In future iterations of the armrest design, the mass of the armrest could be decreased. The decreased mass would result in lower muscle activation requirements to operate the armrest, which may increase its efficacy. Design alterations that may help increase operator comfort include adding a sleeve to help secure the arm to the armrest, and adding lateral adjustment capability, allowing each individual operator to adjust the distance between the chair and armrest.

4.6 References


Chapter 5: Conclusions

The horizontally dynamic armrest addition follows the natural pivoting motion of the forearm during side-to-side joystick movements. A previous validation study indicated that a fore-aft pendulating armrest successfully reduced muscle activation in the shoulder and neck, and pilot work indicated that the side-to-side dynamic armrest addition could reduce muscle activation for those joystick movements as well.

The validation study indicated that the dynamic armrest was successful in reducing the muscle activation in the anterior deltoid, extensor carpi radialis, and in some cases for the upper trapezius and flexor carpi radialis. Using a dynamic armrest did not significantly change upper limb angle ranges when compared to a stationary armrest, and only significantly changed one angle range in the wrist when compared to no armrest. The similar angle ranges indicate operators would not have to alter their natural movement patterns to use the dynamic armrest. Finally, subjects preferred the dynamic armrest overall, and although it was not significant, subjects rated it the most effective armrest during joystick use.

The results indicate that a horizontally dynamic armrest could be a beneficial addition to any workspace where joysticks are used, and likely would be the most effective when paired with a fore-aft dynamic armrest. This dynamic armrest also has several applications outside joystick use. A dynamic armrest could be beneficial in any task where small arm movements are made in a relatively stationary posture such as typing or driving.

5.1 Contributions

The work presented includes the following important contributions to the literature:

1. The unique design of a horizontally dynamic armrest to reduce muscle activation during side-to-side joystick use.
2. The validation of this design, showing that it reduced muscle activation in comparison to a stationary armrest for the wrist extensor muscle during outwards movements, and in some cases for the wrist flexor muscle during inwards movements.
5.2 Recommendations and Future Work

The current dynamic armrest design is functional, but may need to be updated for use in the field. Encasing could be used to protect the bearings from dirt so the armrest movements remain relatively frictionless. Also, subjects in the validation study indicated that the dynamic armrest was more uncomfortable than using no armrest. Many subjects also commented that the location of the armrest was uncomfortable, as it was located too far from the chair for some subjects. Lateral adjustment capability for armrests could help to relieve this. The armrest could be updated to provide more operator comfort by adding springs to soften the stopping points at the endpoints of joystick movement. Adding a sleeve to secure the forearm of each operator instead of the strap used in this study could also increase operator comfort. The design could also be altered to take wrist pronation-supination into account by integrating the slight vertical movement of the wrist during side-to-side joystick manipulation. This would allow the whole forearm to rotate as it does when no armrest is used, which would result in less need for wrist pronation-supination, and could increase operator comfort and further reduce muscle activation. As indicated by the FEA performed during the armrest design, the mass of the armrest could be reduced without compromising the design. This would reduce the required muscle exertion to operate the armrest, which could increase the success of the armrest. Finally, field testing should be carried out to determine whether the armrest is successful while used by experienced joystick operators.
Appendix I: Forms

Consent to Participate in Research

Design and Validation of a Dynamic Armrest

I____________________________________________ am interested in participating in the study ‘Design and validation of a dynamic armrest’ conducted by Principal Investigator Dr. Michele Oliver (University of Guelph) and Ms. Danielle Boucher (University of Guelph). If you have any questions or concerns about the research, please feel free to contact Danielle Boucher at dboucher@uoguelph.ca, or principal investigator Dr. Michele Oliver at (519) 824-4120 ext. 52117 (email: moliver@uoguelph.ca).

PURPOSE OF STUDY
The purpose of this research is to determine if using a dynamic armrest that moves side to side as well as in the forwards and backwards could help to reduce the risk of developing repetitive strain injuries resulting from joystick use.

PROCEDURES
If you volunteer to participate in this study, you will be asked to do the following things. You will initially be asked complete a Physical Activity Readiness Questionnaire and your blood pressure will be measured. You will then be asked to provide information regarding your age, physical activity prior to the experiment, musculoskeletal injury history (if you are currently suffering from or frequently suffer from hand, arm, shoulder, back or neck pain please excuse yourself from this study).

You will then have to conduct a series of maximal reference contractions (MVCs) will be conducted for EMG processing purposes. The MVCs will include three five-second isometric back extensions against resistance while lying prone with their hips and legs secured, isometric trunk curls (to the left, right, and directly anterior to the body) against resistance while the feet are flat, the knees are up, and the ankles are

Subjects will be seated in a mock-up of a mobile machine cab. They will have reflective markers attached to them using double sided tape so that their movements can be tracked and recorded using a VICON® motion capture system. A VICON® motion capture system monitors the location in space of the reflective markers such that things like joystick and joint angles can be calculated. The VICON® system does not involve taking video or pictures so subjects cannot be identified. EMG data will also be collected by placing electrodes on muscles of the arm and trunk using adhesive tape.

Following the placement of the reflective markers and the EMG electrodes, for EMG processing purposes, joystick, task specific isometric maximum voluntary contractions (TMVC) will be collected. TMVCs will be collected from each subject immediately before the commencement of the experiment trials. For each motion direction (left, right, forward backward), subjects will be asked to slowly move the joystick to the endpoint of motion and with vocal encouragement will
be asked to perform a 5 second maximal contraction, focusing on the muscle requirements of the
direction being tested and without additional body contortions. Two TMVCs will be collected for
each direction and a 5-10 minute rest will be given between each motion and test, depending on
the stated fatigue level of the subject.

Following the TMVC procedures, subjects will be asked to perform a series of movements using
a joystick (ie. forward, back, left, right) while using a dynamic armrest, a static armrest and no
armrest. Following data collection subjects will be asked to fill in a questionnaire about their
experience and comfort level using the different joystick. Subject participation will be
completed in approximately 2 hours.

POTENTIAL RISKS AND DISCOMFORTS
You are asked to conduct maximal joystick task based voluntary contractions (TMVC) for the
purpose of electromyographic normalization required during data processing. These maximal
contractions require you to work against there own static limits, but at no time are you
overloaded by external sources. Individuals may develop some latent soreness from this
procedure, which would be comparable to that experienced by individuals initiating a new
exercise regimen. However, for a young healthy male with no prior history of hand, arm,
shoulder, back or neck pain, this should not prove to be any more injurious than their normal
exercise regimen. TMVCs may also place individuals at risk for untoward cardiovascular events.
The subject pool selected combined with the use of cardiovascular screening with the Physical
Activity Readiness Questionnaire and blood pressure measurements means that only low risk
individuals will be allowed to partake in this study, therefore no such events are expected.

You may find the electrodes and reflective markers affixed to your skin with tape to be
uncomfortable and adhesives could result in skin irritation. You are free to withdraw from the
study without fear of reprisal should your skin becomes irritated during the experiment. A skin
lotion will be made available if participants do have skin that becomes irritated. Also, note that
all of the devices attached to you operate at low temperatures and are all covered with a non-
conductive coating to shield you from contact with any electrical currents.

Finally, you will also be required to wear no shirt during the experimental testing. Some
individuls maybe uncomfortable or embarassed with this requirement. If you feel uncomfortable
or feel embarassed at any point during the testing session you are free to terminate and leave the
study.

Be assured that all information obtained for the study will be confidential and that no
mention of participant names will ever be used.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY
The results of this study will help to determine if a dynamic armrest could be used to
reduce muscle activation requirements in order to reduce repetitive strain injury
development risk. The results will be used to make recommendations for heavy equipment
seat and armrest design.

CONFIDENTIALITY
Every effort will be made to ensure confidentiality of any identifying information that is obtained in connection with this study. Only members of the research team will have access to the data collected, and all information obtained will be strictly confidential. You will be given an ID number to keep track of the various forms of data collected, but absolutely no identifying information will be recorded (i.e. names, employee ID numbers, SIN, etc.). Your name will be linked to the ID number in the consent form, but all other data will be stored separately and will be linked to the ID number only, thus protecting your confidentiality. The consent form will be locked in a filing cabinet, kept for a period of five year after which it will be destroyed.

PARTICIPATION AND WITHDRAWAL
You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may exercise the option of removing your data from the study. You may also refuse to answer any questions you don’t want to answer and still remain in the study.

There are two copies of this consent form; one which the researcher keeps and one that I keep.

RIGHTS OF RESEARCH PARTICIPANTS
You may withdraw your consent at anytime and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this study. This study has been reviewed and received ethics clearance through the University of Guelph Research Ethics Board. If you have questions regarding your rights as a research participant, contact:

Research Ethics Officer  Telephone: (519) 824-4120 ext. 56606
University of Guelph  E-mail: sauld@uoguelph.ca
437 University Center  Fax: (519) 821-5236
Guelph, ON, N1G 2W1

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE
I have read the information provided for the study ‘Design and Validation of a Dynamic Armrest’ as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

________________________________________
Name of Participant (please print)

________________________________________
Name of Legal Representative (if applicable)

________________________________________
Signature of Participant or Legal Representative  Date
SIGNATURE OF WITNESS

_________________________________________
Name of Witness (please print)

_________________________________________
Signature of Witness                       Date

If you would like a copy of the results from this research study please provide us with your email address below.

Email: ________________________________
Questionnaire for Dynamic Armrest Study

No Armrest
Please indicate on the graphical scale the level of:

a) Perceived effort

[Graphical scale]

none hardly noticeable moderate somewhat difficult tremendous

b) Perceived discomfort

[Graphical scale]

none faint somewhat moderate somewhat uncomfortable tremendous

Standard Armrest
Please indicate on the graphical scale the level of:

a) Perceived effort

[Graphical scale]

none hardly noticeable moderate somewhat difficult tremendous

b) Perceived discomfort

[Graphical scale]

none faint somewhat moderate somewhat uncomfortable tremendous

c) Overall effectiveness of the arm support

[Graphical scale]

not ineffective slightly moderately slightly adequate effective

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Dynamic Armrest

Please indicate on the graphical scale the level of:

a) Perceived effort

[Graphical Scale]

none hardly noticeable moderate somewhat difficult tremendous

b) Perceived discomfort

[Graphical Scale]

none faint somewhat moderate somewhat uncomfortable tremendous

c) Overall effectiveness of the arm support

[Graphical Scale]

not ineffective slightly moderately slightly adequate effective

Overall Preference

Indicate your preference of arm supports by circling one of the following:

No Arm Support  Standard Arm Support  Dynamic Arm Support
<table>
<thead>
<tr>
<th>Appendices</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>pg 88</td>
</tr>
<tr>
<td>Inner Arm</td>
<td>pg 89</td>
</tr>
<tr>
<td>Outer Arm</td>
<td>pg 90</td>
</tr>
<tr>
<td>Assembly</td>
<td>pg 91</td>
</tr>
</tbody>
</table>
Appendix III: Custom Matlab® Programs

Note – all code for subject ‘L’, subject name changed accordingly for processing other subject data

Pilot Work: EMG

Emg_main.m

%This is a program that Linear envelopes EMG data  
%Created February 21, 2012

clear
close all
dummy=0;

%Linear envelope data
[bicep_s,tricep_s,AD_s,PD_s,UT_s]=envelope_a(dummy);
[bicep_us,tricep_us,AD_us,PD_us,UT_us]=envelope_b(dummy);

time=1:10000;

%Find iEMG using trapezoidal integration
Int_bi_un=trapz(time,bicep_us);
Int_bi_s=trapz(time,bicep_s);
Int_t_un=trapz(time,tricep_us);
Int_t_s=trapz(time,tricep_s);
Int_ad_un=trapz(time,AD_us);
Int_ad_s=trapz(time,AD_s);
Int_pd_un=trapz(time,PD_us);
Int_pd_s=trapz(time,PD_s);
Int_ut_un=trapz(time,UT_us);
Int_ut_s=trapz(time,UT_s);

%Find pEMG
max_bi_un=max(bicep_us);
max_bi_s=max(bicep_s);
max_t_un=max(tricep_us);
max_t_s=max(tricep_s);
max_ad_un=max(AD_us);
max_ad_s=max(AD_s);
max_pd_un=max(PD_us);
max_pd_s=max(PD_s);
max_ut_un=max(UT_us);
max_ut_s=max(UT_s);

%Output iEMG and pEMG values
fprintf('Title
');
fprintf('
 iEMG Unsupported    Bicep   Tricep  AD  PD
UT
');
fprintf('%.3f %8.3f %8.3f %8.3f

Supported
');
fprintf('%.3f %8.3f %8.3f %8.3f %8.3f
',Int_bi_s,Int_t_s,Int_ad_s,Int_pd_s,Int_ut_s);
fprintf('n Peak EMG Unsupported    Bicep  Tricep  AD  PD  UT
');
fprintf('%.3f %8.3f %8.3f %8.3f %8.3f
',max_bi_un,max_t_un,max_ad_un,max_pd_un,max_ut_un);
fprintf('n Supported
');
fprintf('%.3f %8.3f %8.3f %8.3f %8.3f
',max_bi_s,max_t_s,max_ad_s,max_pd_s,max_ut_s);

%Plot linear envelope emg
figure(2)
set(gcf, 'DefaultLineLineWidth',1.5)
set(gcf, 'DefaultTextFontsize',12)
subplot(5,1,1),plot(time,bicep_s,time,bicep_us,'--');
axis([0 10000 0 0.03]);
ylabel('Biceps (mV)','fontsize',12);
subplot(5,1,2),plot(time,tricep_s,time,tricep_us,'--');
axis([0 10000 0 0.02]);
ylabel('Triceps (mV)','fontsize',12);
subplot(5,1,3),plot(time,AD_s,time,AD_us,'--');
ylabel('Anterior Deltoid (mV)','fontsize',12);
subplot(5,1,4),plot(time,PD_s,time,PD_us,'--');
ylabel('Posterior Deltoid (mV)');
subplot(5,1,5),plot(time,UT_s,time,UT_us,'--');
ylabel('Upper Trapezius (mV)','fontsize',12);
xlabel('Time (s)','fontsize',12);
legend('Supported','Unsupported');

---

envelope_a.m

Note: envelope_b/m not shows as it is very similar to envelope_a.m

function [bicep_envelope,tricep_envelope,AD_envelope,PD_envelope,UT_envelope,h ]=envelope_a(dummy)
%This is a program that Linear enveloped EMG data
%Created February 21, 2012

%Load EMG data
load s4.txt
emgraw=s4;

%Bandpass Filter raw EMG
[b,a]=butter(2,400/500,'low');
emglow=filtfilt(b,a,emgraw);
[b,a]=butter(2,20/500,'high');
emg=filtfilt(b,a,emglow);

%Load EMG2 data
load ss2.txt
emgraw2=ss2;

%Bandpass Filter raw EMG
[b,a]=butter(2,400/500,'low');
emglow2=filtfilt(b,a,emgraw2);
[b,a]=butter(2,20/500,'high');
emg2=filtfilt(b,a,emglow2);

%Create Vectors of EMG for each muscle
bicep=emg(:,2);
tricep=emg(:,3);
PD=emg(:,5);
AD=emg(:,4);
UT=emg2(:,4);

%Process EMG
absbicep=abs(bicep);
abstricep=abs(tricep);
absAD=abs(AD);
absPD=abs(PD);
absUT=abs(UT);

%Create 6 Hz linear envelope
[b,a]=butter(2,6/500,'low');
bi=filtfilt(b,a,absbicep);
tr=filtfilt(b,a,abstricep);
AD=filtfilt(b,a,absAD);
PD=filtfilt(b,a,absPD);
UT=filtfilt(b,a,absUT);

%Cleave data
[indicesut]=cleave(UT);
[indices]=cleave(bi);
bicep_envelope=bi(indices);
tricep_envelope=tr(indices);
AD_envelope=AD(indices);
PD_envelope=PD(indices);
UT_envelope=UT(indicesut);

Cleave.m

function [indices]=cleave(arvariables)

%This function normalizes the length of the data variables
%to be 10,000 units long in order to allow the unsupported and
%supported emg data to be plotted on the same graph

[howbig,dummy]=size(arvariables);

for i=1:10000
    xb(i)=floor((howbig*i)/10000);
    if xb(i)==0
        xb(i)=1;
    end
end
indices=xb;

**Pilot Work: Motion Capture**

**Main.m**

```matlab
% This program will chop and average wrist trajectories for left-right
% joystick movements
% Danielle Boucher
% July 9 2012

clear all;
close all;

% Load 4 files,
for i=1:5;
    eval(['m' num2str(i) '=load(''m'' num2str(i) '.txt'');']);
end;

% Reorder based on file
[rm1]=reorder14(m1);
[rm2]=reorder23(m2);
[rm3]=reorder23(m3);
[rm4]=reorder14(m4);
[rm5]=reorder23(m5);

% Cleave to joystick movement
for i=1:5;
    eval(['subplot(1,1,1),plot(rm' num2str(i) '(:,1)); '])
ylabel ('joystick');
points=2;
[X,Y]=ginput(points);
X=floor(X);
    eval(['cm' num2str(i) '=rm' num2str(i) '(X(1,1):X(2,1,:),:);'])
end

% Find ranges for each dataset
[g1]=ranges(cm1);
[g2]=ranges(cm2);
[g3]=ranges(cm3);
[g4]=ranges(cm4);
[g5]=ranges(cm5);
ranges=[g1,g2,g3,g4,g5];

% Normalize length and average files
[am,sd]=average(cm1,cm2,cm3,cm4,cm5);

%Output results
dlmwrite('Results.txt',am,'delimiter','\t','newline','pc');
dlmwrite('SD.txt',sd,'delimiter','\t','newline','pc');
dlmwrite('Ranges.txt',ranges,'delimiter','\t','newline','pc');
```
reorder14.m

Note: reorder34.m not shown, as it is very similar to reorder14.m

`function [r] = reorder14(cm)`

% This function reorders the Vicon data so that all columns are in the same
% order
% Danielle Boucher
% July 9 2012

% Label Columns
joyx = cm(:,20);
elbx = cm(:,8);
elby = cm(:,9);
elbz = cm(:,10);
wrix = cm(:,14);
wriy = cm(:,15);
wriz = cm(:,16);

% Recombine
r = [joyx, elbx, elby, elbz, wrix, wriy, wriz];

ranges.m

`function [g] = ranges(cm)`

% This program finds the range in mm in each direction (x,y,z) of the elbow
% and wrist markers
% Danielle Boucher
% July 9, 2012

% Label Columns
elbx = cm(:,2);
elby = cm(:,3);
elbz = cm(:,4);
wrix = cm(:,5);
wriy = cm(:,6);
wriz = cm(:,7);

% Find max and min displacement values
exmax = max(elbx);
eymax = max(elby);
ezmax = max(elbz);
wxmax = max(wrix);
wymax = max(wriy);
wzmax = max(wriz);
exmin = min(elbx);
eymin = min(elby);
ezmin = min(elbz);
wxmin = min(wrix);
wxmin = min(wriy);
wzmin = min(wriz);

% Find Ranges
ex=(exmax-exmin);
ey=(eymax-eymin);
ez=(ezmax-ezmin);
wx=(wxmax-wxmin);
wy=(wymax-wymin);
wz=(wzmax-wzmin);

g=[ex,ey,ez,wx,wy,wz];

average.m

Refer to average.m in Appendix III: Motion Capture Code.

EMG Code

MainL.m

% Main program, processes all EMG files for one subject,
% as well as forces on the joystick
% Danielle Boucher
% April 17 2012
% edited April 25th, June 21, 2012

clear all;
close all;

%load and relabel MVC’s
load LF.txt;
forward = LF;
load LB.txt;
back = LB;
load LI.txt;
in = LI;
load LO.txt;
out = LO;

%DYNAMIC ARMREST
%Load 12 trials, find max strain gauge force, FB (column2)
%or LR (column 3)
for i=1:12;
    eval(['LD' num2str(i) '=load(''LD' num2str(i) '.txt'');']);
    if i<=3 %forwards
        eval(['maxd' num2str(i) '=max(LD' num2str(i) '(:,2));']);
    elseif i>3 && i<=6 %back
        eval(['maxd' num2str(i) '=min(LD' num2str(i) '(:,2));']);
    elseif i>6 && i<=9 %in
        eval(['maxd' num2str(i) '=min(LD' num2str(i) '(:,3));']);
    else %out
        eval(['maxd' num2str(i) '=max(LD' num2str(i) '(:,3));']);
    end
end;

%Run processemg.m which returns linear enveloped EMG, and time of trial
%starting and ending in neutral joystick position
[EMG1,dt1]=processemg2(LD1,forward);
[EMG2,dt2]=processemg2(LD2,forward);
[EMG3,dt3]=processemg2(LD3,forward);
[EMG4,dt4]=processemg2(LD4,back);
[EMG5,dt5]=processemg2(LD5,back);
[EMG6,dt6]=processemg2(LD6,back);
[EMG7,dt7]=processemg2(LD7,in);
[EMG8,dt8]=processemg2(LD8,in);
[EMG9,dt9]=processemg2(LD9,in);
[EMG10,dt10]=processemg2(LD10,out);
[EMG11,dt11]=processemg2(LD11,out);
[EMG12,dt12]=processemg2(LD12,out);

%Run average.m which normalizes length of 3 trials and averages them,
%returns averaged EMG, peak, and iEMG
[EMG_DF,peakDF,iemgDF]=average3(EMG1,EMG2,EMG3);
[EMG_DB,peakDB,iemgDB]=average3(EMG4,EMG5,EMG6);
[EMG_DI,peakDI,iemgDI]=average3(EMG7,EMG8,EMG9);
[EMG_DO,peakDO,iemgDO]=average3(EMG10,EMG11,EMG12);

%Find average max force for each set of conditions, and apply calibration
%equation
maxdf = (maxd1 + maxd2 + maxd3)/3;
forcedf = (154.59 * maxdf) - 7.4696;
maxdb = (maxd4 + maxd5 + maxd6)/3;
forcedb = (154.59 * maxdb) - 7.4696;
maxdi = (maxd7 + maxd8 + maxd9)/3;
forcedi = (164.69 * maxdi) - 16.66;
maxdo = (maxd10 + maxd11 + maxd12)/3;
forcedo = (164.69 * maxdo) - 16.66;

%STATIONARY ARMREST
for i=1:12;
  eval(['LS' num2str(i) ' =load(''LS'' num2str(i) ' .txt'');']);
  if i<=3 %forwards
    eval(['maxs' num2str(i) ' =max(LS' num2str(i) ' (:,2));']);
  elseif i>3 && i<=6 %back
    eval(['maxs' num2str(i) ' =min(LS' num2str(i) ' (:,2));']);
  elseif i>6 && i<=9 %in
    eval(['maxs' num2str(i) ' =min(LS' num2str(i) ' (:,3));']);
  else %out
    eval(['maxs' num2str(i) ' =max(LS' num2str(i) ' (:,3));']);
  end
end;

[EMG1,st1]=processemg2(LS1,forward);
[EMG2,st2]=processemg2(LS2,forward);
[EMG3,st3]=processemg2(LS3,forward);
[EMG4,st4]=processemg2(LS4,back);
[EMG5,st5]=processemg2(LS5,back);
[EMG6,st6]=processemg2(LS6,back);
[EMG7,st7]=processemg2(LS7,in);
[EMG8,st8]=processemg2(LS8,in);
[EMG9,st9]=processemg2(LS9,in);
[EMG10,st10]=processemg2(LS10,out);
\[ \text{[EMG11, st11]} = \text{processemg2}(\text{LS11, out}); \]
\[ \text{[EMG12, st12]} = \text{processemg2}(\text{LS12, out}); \]
\[ \text{[EMG}_{SF}, \text{peakSF}, \text{iemgSF]} = \text{average3} (\text{EMG1, EMG2, EMG3}); \]
\[ \text{[EMG}_{SB}, \text{peakSB}, \text{iemgSB]} = \text{average3} (\text{EMG4, EMG5, EMG6}); \]
\[ \text{[EMG}_{SI}, \text{peakSI}, \text{iemgSI]} = \text{average3} (\text{EMG7, EMG8, EMG9}); \]
\[ \text{[EMG}_{SO}, \text{peakSO}, \text{iemgSO]} = \text{average3} (\text{EMG10, EMG11, EMG12}); \]

\[
\text{maxsf} = (\text{maxs1} + \text{maxs2} + \text{maxs3})/3; \\
\text{forcesf} = (154.59 \times \text{maxsf}) - 7.4696; \\
\text{maxsb} = (\text{maxs4} + \text{maxs5} + \text{maxs6})/3; \\
\text{forcesb} = (154.59 \times \text{maxsb}) - 7.4696; \\
\text{maxsi} = (\text{maxs7} + \text{maxs8} + \text{maxs9})/3; \\
\text{forcesi} = (164.69 \times \text{maxsi}) - 16.66; \\
\text{maxso} = (\text{maxs10} + \text{maxs11} + \text{maxs12})/3; \\
\text{forceso} = (164.69 \times \text{maxso}) - 16.66; \\
\]

% NO ARMREST
for \( i = 1:12; \)
\[
\text{eval('[LN' num2str(i) ' = load(''LN' num2str(i) '.txt'');']);} \\
\text{if} \ i < 3 \ %\text{forwards} \\
\text{eval('[maxn' num2str(i) ' = max(LN' num2str(i) '(:,2));']);} \\
\text{elseif} \ i > 3 \ & \ i < 6 \ %\text{back} \\
\text{eval('[maxn' num2str(i) ' = min(LN' num2str(i) '(:,2));']);} \\
\text{elseif} \ i > 6 \ & \ i < 9 \ %\text{in} \\
\text{eval('[maxn' num2str(i) ' = min(LN' num2str(i) '(:,3));']);} \\
\text{else} \ %\text{out} \\
\text{eval('[maxn' num2str(i) ' = max(LN' num2str(i) '(:,3));']);} \\
\text{end} \\
\end{for}

\[ \text{[EMG1, nt1]} = \text{processemg2}(\text{LN1, forward}); \]
\[ \text{[EMG2, nt2]} = \text{processemg2}(\text{LN2, forward}); \]
\[ \text{[EMG3, nt3]} = \text{processemg2}(\text{LN3, forward}); \]
\[ \text{[EMG4, nt4]} = \text{processemg2}(\text{LN4, back}); \]
\[ \text{[EMG5, nt5]} = \text{processemg2}(\text{LN5, back}); \]
\[ \text{[EMG6, nt6]} = \text{processemg2}(\text{LN6, back}); \]
\[ \text{[EMG7, nt7]} = \text{processemg2}(\text{LN7, in}); \]
\[ \text{[EMG8, nt8]} = \text{processemg2}(\text{LN8, in}); \]
\[ \text{[EMG9, nt9]} = \text{processemg2}(\text{LN9, in}); \]
\[ \text{[EMG10, nt10]} = \text{processemg2}(\text{LN10, out}); \]
\[ \text{[EMG11, nt11]} = \text{processemg2}(\text{LN11, out}); \]
\[ \text{[EMG12, nt12]} = \text{processemg2}(\text{LN12, out}); \]
\[ \text{[EMG}_{NF}, \text{peakNF}, \text{iemgNF]} = \text{average3} (\text{EMG1, EMG2, EMG3}); \]
\[ \text{[EMG}_{NB}, \text{peakNB}, \text{iemgNB]} = \text{average3} (\text{EMG4, EMG5, EMG6}); \]
\[ \text{[EMG}_{NI}, \text{peakNI}, \text{iemgNI]} = \text{average3} (\text{EMG7, EMG8, EMG9}); \]
\[ \text{[EMG}_{NO}, \text{peakNO}, \text{iemgNO]} = \text{average3} (\text{EMG10, EMG11, EMG12}); \]

\[
\text{maxnf} = (\text{maxn1} + \text{maxn2} + \text{maxn3})/3; \\
\text{forcenf} = (154.59 \times \text{maxnf}) - 7.4696; \\
\text{maxnb} = (\text{maxn4} + \text{maxn5} + \text{maxn6})/3; \\
\text{forcenb} = (154.59 \times \text{maxnb}) - 7.4696; \\
\text{maxni} = (\text{maxn7} + \text{maxn8} + \text{maxn9})/3; \\
\text{forceni} = (164.69 \times \text{maxni}) - 16.66; \\
\text{maxno} = (\text{maxn10} + \text{maxn11} + \text{maxn12})/3; \\
\]
forceno = (164.69 * maxno) - 16.66;

%Combine trial times, output to text file
timed= [dt1,dt2,dt3,dt4,dt5,dt6,dt7,dt8,dt9,dt10,dt11,dt12];
times= [st1,st2,st3,st4,st5,st6,st7,st8,nt9,nt10,nt11,nt12];
timen= [nt1,nt2,nt3,nt4,nt5,nt6,nt7,nt8,nt9,nt10,nt11,nt12];
timetrial=[timed',times',timen'];
dlmwrite('Ltimes.txt',timetrials,'delimiter','\t','newline','pc');

%Combine and output to text files peak and iEMG
LPoutput=[peakDF,peakDB,peakDI,peakDO,peakSF,peakSB,peakSI,peakSO,peakNF,peakNB,peakNI,peakNO];
LIoutput=[iemgDF,iemgDB,iemgDI,iemgDO,iemgSF,iemgSB,iemgSI,iemgSO,iemgNF,iemgNB,iemgNI,iemgNO];
dlmwrite('LPoutput.txt',LPoutput,'delimiter','\t','newline','pc');
dlmwrite('LIoutput.txt',LIoutput,'delimiter','\t','newline','pc');

%Combine and output Forces
Lforces=[forcef,forceb,forcei,forceo,forcedf,forcedb,forcedi,forcedo,forcesf,forcesb,forcesi,forceso,forcenf,forcenb,forceni,forceno];
dlmwrite('Lforces.txt',Lforces,'delimiter','\t','newline','pc');

function [EMG, time] = processegm2(analog, MVC)
%This function will fully analyze one trial of EMG data:
%bandpass EMG, normalize, linear envelope, and cleave data
%Danielle Boucher
%April 17, 2012

%Label input EMG columns
FB = analog(:,2);
LR = analog(:,3);
B = analog(:,4);
T = analog(:,5);
AD = analog(:,6);
PD = analog(:,7);
UT = analog(:,8);
Pec = analog(:,9);
FCR = analog(:,10);
ECR = analog(:,11);

%Create new files for EMG and joystick
rawEMG = [B,T,AD,PD,UT,Pec,FCR,ECR];
JOY = [FB,LR];

%Bandpass filter EMG btw 20 and 400 Hz
[a,b]=butter(2,400/500,'low');
emglow=filtfilt(a,b,rawEMG);
[a,b]=butter(2,20/500,'high');
EMG=filtfilt(a,b,emglow);

%Normalize EMG
[normEMG]=normalize(EMG, MVC);
% Process EMG, 6Hz linear envelope
[a,b]=butter(2,6/500,'low');
envemg=filtfilt(a,b,normEMG);

% Choose points to cleave to according to joystick starin gauge output
subplot(2,1,1),plot(JOY(:,1));
ylabel('FB');
subplot(2,1,2),plot(JOY(:,2));
ylabel('IO');
points=2;
[X,Y]=ginput(points);
X=floor(X);

% Cleave EMG data
EMG=envemg(X(1,1):X(2,1),:);

% Determine time each trial took
[r,c]=size(EMG);
time=r/1000;

Normalize.m

function[normEMG]=normalize(rawEMG,MVC)
% This program normalizes EMG data by finding the peak for each muscle in
% the MVC trial and outputting EMG from all other files as a percentage of
% this.
% Danielle Boucher
% April 12, 2012
% Edited April 25, 2012

% Bandpass filter MVC btw 20 and 400 Hz
[a,b]=butter(2,400/500,'low');
mvcclow=filtfilt(a,b,MVC);
[a,b]=butter(2,20/500,'high');
mvcfilt=filtfilt(a,b,mvcclow);

% Label each column
mvcB=mvcfilt(:,4);
mvcT=mvcfilt(:,5);
mvcAD=mvcfilt(:,6);
mvcPD=mvcfilt(:,7);
mvcUT=mvcfilt(:,8);
mvcPec=mvcfilt(:,9);
mvcFCR=mvcfilt(:,10);
mvcECR=mvcfilt(:,11);

% Find peak of absolute value of each
pB=max(abs(mvcB));
pT=max(abs(mvcT));
pAD=max(abs(mvcAD));
pPD=max(abs(mvcPD));
pUT=max(abs(mvcUT));
pPec=max(abs(mvcPec));
pFCR=max(abs(mvcFCR));
pECR=max(abs(mvcECR));

%Label data input columns
B=rawEMG(:,1);
T=rawEMG(:,2);
AD=rawEMG(:,3);
PD=rawEMG(:,4);
UT=rawEMG(:,5);
Pec=rawEMG(:,6);
FCR=rawEMG(:,7);
ECR=rawEMG(:,8);

%Normalize, full wave rectify raw EMG and divide by peak MVC for each muscle
nB=(abs(B))/pB;
nT=(abs(T))/pT;
nAD=(abs(AD))/pAD;
nPD=(abs(PD))/pPD;
nUT=(abs(UT))/pUT;
nPec=(abs(Pec))/pPec;
nFCR=(abs(FCR))/pFCR;
nECR=(abs(ECR))/pECR;

%Recombine normalized data
normEMG=[nB,nT,nAD,nPD,nUT,nPec,nFCR,nECR];

function [EMG_avg, peak, iemg] = average3(EMG_1, EMG_2, EMG_3)
%This program calculates iEMG and pEMG WITHOUT normalizing length and averaging 3 EMG graphs
%Danielle Boucher
%Created April 18, 2012
%Edited July 30, 2012, July 20, 2012

clear

%Calculate iEMG for each file with respect to time
for i=1:3;
    load time.txt;
    eval(['[r,c]=size(EMG_ num2str(i) ');'])
    time(r+1:6000,:)=[]; %Resize time file
    %Trapezoidal integration, multiplied by 100 to express as a %
    eval(['iB=trapz(time,EMG_ num2str(i) ' '(;1)*100);'])
    eval(['iT=trapz(time,EMG_ num2str(i) ' '(;2)*100);'])
    eval(['iAD=trapz(time,EMG_ num2str(i) ' '(;3)*100);'])
    eval(['iPD=trapz(time,EMG_ num2str(i) ' '(;4)*100);'])
    eval(['iUT=trapz(time,EMG_ num2str(i) ' '(;5)*100);'])
    eval(['iPec=trapz(time,EMG_ num2str(i) ' '(;6)*100);'])
    eval(['iFCR=trapz(time,EMG_ num2str(i) ' '(;7)*100);'])
    eval(['iECR=trapz(time,EMG_ num2str(i) ' '(;8)*100);'])
eval(['iemg' num2str(i) '=[iB,iT,iAD,iPD,iUT,iPec,iFCR,iECR];'])

%Peak EMG, maximum value, multiplied by 100 to express as a %
eval(['mB=(max(EMG_' num2str(i) '(:,1))*100);'])
eval(['mT=(max(EMG_' num2str(i) '(:,2))*100);'])
eval(['mAD=(max(EMG_' num2str(i) '(:,3))*100);'])
eval(['mPD=(max(EMG_' num2str(i) '(:,4))*100);'])
eval(['mUT=(max(EMG_' num2str(i) '(:,5))*100);'])
eval(['mPec=(max(EMG_' num2str(i) '(:,6))*100);'])
eval(['mFCR=(max(EMG_' num2str(i) '(:,7))*100);'])
eval(['mECR=(max(EMG_' num2str(i) '(:,8))*100);'])
eval(['peak' num2str(i) '=[mB,mT,mAD,mPD,mUT,mPec,mFCR,mECR];'])
end

%Recombine iEMG and pEMG's
iemg=(iemg1+iemg2+iemg3)/3;
peak=(peak1+peak2+peak3)/3;

%Normalize all to length 3000
for i=1:3;
  for t=1:3000;
    eval(['index(t)=floor(((length(EMG_' num2str(i) '))+t)/3000);'])
    if index(t)==0;
      index(t)=1;
    end;
  end;
  index=index';

%Label Columns
eval(['B' num2str(i) '=EMG_' num2str(i) '(:,1);'])
eval(['T' num2str(i) '=EMG_' num2str(i) '(:,2);'])
eval(['AD' num2str(i) '=EMG_' num2str(i) '(:,3);'])
eval(['PD' num2str(i) '=EMG_' num2str(i) '(:,4);'])
eval(['UT' num2str(i) '=EMG_' num2str(i) '(:,5);'])
eval(['Pec' num2str(i) '=EMG_' num2str(i) '(:,6);'])
eval(['FCR' num2str(i) '=EMG_' num2str(i) '(:,7);'])
eval(['ECR' num2str(i) '=EMG_' num2str(i) '(:,8);'])

%Index columns
eval(['B' num2str(i) '=B' num2str(i) '((index));'])
eval(['T' num2str(i) '=T' num2str(i) '((index));'])
eval(['AD' num2str(i) '=AD' num2str(i) '((index));'])
eval(['PD' num2str(i) '=PD' num2str(i) '((index));'])
eval(['UT' num2str(i) '=UT' num2str(i) '((index));'])
eval(['Pec' num2str(i) '=Pec' num2str(i) '((index));'])
eval(['FCR' num2str(i) '=FCR' num2str(i) '((index));'])
eval(['ECR' num2str(i) '=ECR' num2str(i) '((index));'])
end

%Average each muscle
B_avg=(B1+B2+B3)/3;
T_avg=(T1+T2+T3)/3;
AD_avg=(AD1+AD2+AD3)/3;
PD_avg = (PD1 + PD2 + PD3) / 3;
UT_avg = (UT1 + UT2 + UT3) / 3;
Pec_avg = (Pec1 + Pec2 + Pec3) / 3;
FCR_avg = (FCR1 + FCR2 + FCR3) / 3;
ECR_avg = (ECR1 + ECR2 + ECR3) / 3;

% Recombine
EMG_avg = [B_avg, T_avg, AD_avg, PD_avg, UT_avg, Pec_avg, FCR_avg, ECR_avg];

---

**Motion Capture Code**

**Maincleave.m**

```
% This program will cleave all VICON files, determine angles, and angle ranges for the shoulder, elbow, wrist and joystick
% June 12 2012
% Danielle Boucher

clear all;
close all;

% Load files, process VICON, find angles
% DYNAMIC ARMREST
for i=1:12;
    eval(['VLD' num2str(i) '=load(''VLD' num2str(i) '.txt'');']);
    eval(['[r' num2str(i) ',c' num2str(i) ']=size(VLD' num2str(i) ' ');']);
    eval(['r' num2str(i) '=100*(ceil(r' num2str(i) '/100));']);

    % Choose points and cleave data based on joystick marker movement
    eval(['subplot(4,1,1),plot(VLD' num2str(i) '(:,9)); '])
ylabel ('FB');
title ('D');
    eval(['subplot(4,1,2),plot(VLD' num2str(i) '(:,8));'])
ylabel ('IO');
    eval(['subplot(4,1,3),plot(VLD' num2str(i) '(:,14));'])
    eval(['subplot(4,1,4),plot(VLD' num2str(i) '(:,15));'])
points=2;
    [X,Y]=ginput(points);
    X=floor(X);
    eval(['cVLD' num2str(i) '=VLD' num2str(i) '(:,1);X(1,1):X(2,1),:);'])

    % Determine angles for x, y, and z
    eval(['[xang' num2str(i) ']=anglesx(cVLD' num2str(i) ');']);
    eval(['[yang' num2str(i) ']=anglesy(cVLD' num2str(i) ');']);
    eval(['[zang' num2str(i) ']=anglesz(cVLD' num2str(i) ');']);

    % Combine x, y, and z angles
    eval(['ANG' num2str(i) '=[xang' num2str(i) ',yang' num2str(i) ',zang' num2str(i) ']';'])
end;

% Outputs averaged angle curves, max, and min angle
[avgDF,xdf,ndf]=average(ANG1,ANG2,ANG3);
```
[avgDB, xdb, ndb] = average(ANG4, ANG5, ANG6);
[avgDI, xdi, ndi] = average(ANG7, ANG8, ANG9);
[avgDO, xdo, ndo] = average(ANG10, ANG11, ANG12);

clear points;

% STATIONARY ARMREST
for i = 1:12;
    eval(['VLS' num2str(i) '=load('''VLS' num2str(i) '.txt'');'])
    eval(['[r' num2str(i) ',c' num2str(i) '] = size(VLS' num2str(i) ');'])
    eval(['[r' num2str(i) ']=100*(ceil(r' num2str(i) '/100));'])

    eval(['subplot(4,1,1),plot(VLS' num2str(i) '(:,9)); '])
    ylabel ('FB');
    title ('S');
    eval(['subplot(4,1,2),plot(VLS' num2str(i) '(:,8));'])
    ylabel ('IO');
    eval(['subplot(4,1,3),plot(VLS' num2str(i) '(:,14));'])
    eval(['subplot(4,1,4),plot(VLS' num2str(i) '(:,15));'])
    points = 2;
    [X, Y] = ginput(points);
    X = floor(X);
    eval(['cVLS' num2str(i) '=VLS' num2str(i) '(X(1,1):X(2,1),:);'])
    eval(['[xang' num2str(i) '=anglesx(cVLS' num2str(i) ');'])
    eval(['[yang' num2str(i) '=anglesy(cVLS' num2str(i) ');'])
    eval(['[zang' num2str(i) '=anglesz(cVLS' num2str(i) ');'])

    eval(['ANG' num2str(i) '=[xang' num2str(i) ',yang' num2str(i) ',zang' num2str(i) '];'])
end;

[avgSF, xsf, nsf] = average(ANG1, ANG2, ANG3);
[avgSB, xsb, nsb] = average(ANG4, ANG5, ANG6);
[avgSI, xsi, nsi] = average(ANG7, ANG8, ANG9);
[avgSO, xso, nso] = average(ANG10, ANG11, ANG12);

clear points;

% NO ARMREST
for i = 1:11;
    eval(['VLAN' num2str(i) '=load('''VLAN' num2str(i) '.txt'');'])
    eval(['[r' num2str(i) ',c' num2str(i) '] = size(VLAN' num2str(i) ');'])
    eval(['[r' num2str(i) ']=100*(ceil(r' num2str(i) '/100));'])

    eval(['subplot(4,1,1),plot(VLAN' num2str(i) '(:,9)); '])
    ylabel ('FB');
    title ('N');
    eval(['subplot(4,1,2),plot(VLAN' num2str(i) '(:,8));'])
    ylabel ('IO');
    eval(['subplot(4,1,3),plot(VLAN' num2str(i) '(:,14));'])
    eval(['subplot(4,1,4),plot(VLAN' num2str(i) '(:,15));'])
    points = 2;
    [X, Y] = ginput(points);
\[ X = \text{floor}(X); \]
\[
\text{eval([''cVLN'' num2str(i) ''] = VLN' num2str(i) ',(X(1,1):X(2,1,:),:);}');']
\]
\[
\text{eval([''[xang' num2str(i) ''] = anglesx(cVLN' num2str(i) ');}');']
\[
\text{eval([''[yang' num2str(i) ''] = anglesy(cVLN' num2str(i) ');}');']
\[
\text{eval([''[zang' num2str(i) ''] = anglesz(cVLN' num2str(i) ');}');']
\]
\[
\text{eval([''ANG' num2str(i) ''] = [''xang' num2str(i) '' ,yang' num2str(i) '' ,zang' num2str(i) '']);']
\]
\[
\]end;\]
\[
[\text{avgNF},xnf,nnf]=\text{average}(ANG1,ANG2,ANG3);\]
\[
[\text{avgNB},xnb,nnb]=\text{average}(ANG4,ANG5,ANG6);\]
\[
[\text{avgNI},xni,nni]=\text{average2}(ANG7,ANG8);\]
\[
[\text{avgNO},xno,nno]=\text{average}(ANG9,ANG10,ANG11);\]

%Combine and output angle ranges
\[
\text{maxes}=[xdf',xdb',xdi',xdo',xsf',xsb',xisi',xso',xnf',xnb',xni',xno'];\]
\[
\text{mins}=[ndf',ndb',ndi',ndo',nsf',nsb',nsi',nso',nnf',nnb',nni',nno'];\]
\[
\text{AngRange}=\text{maxes}-\text{mins};\]
\[
\text{dlmwrite('Max.txt',maxes,'delimiter','\t','newline','pc');}\]
\[
\text{dlmwrite('Min.txt',mins,'delimiter','\t','newline','pc');}\]
\[
\text{dlmwrite('AngRange.txt',AngRange,'delimiter','\t','newline','pc');}\]

**Anglesx.m**

Note – similar programs for y and z planes (anglesy.m and anglesz.m) not shown. They are replicas of this program with marker input column numbers changed.

**function** [output]=anglesx(input)

%This program finds the angles of the right arm in the yz plane using dot product.
%Danielle Boucher
%May 22, 2012

v=input;

%Determine wrist center location: (WRA-WRB)/2
wristy=(v(:,18)+v(:,21))/2;
wristz=(v(:,19)+v(:,22))/2;

%Elbow Angle: elb-wri y z, elb-sho y z
EW(:,1)=v(:,12)-wristy;
EW(:,2)=v(:,13)-wristz;
ES(:,1)=v(:,12)-v(:,3);
ES(:,2)=v(:,13)-v(:,4);

%Wrist Angle: Wri-fin y z, wri-elb y z
WF(:,1)=wristy-v(:,15);
WF(:,2)=wristz-v(:,16);
WE(:,1)=wristy-v(:,12);
WE(:,2)=wristz-v(:,13);
Shoulder angle: sho-torso y z, sho-elb y z
ST(:,1)=v(:,3)-v(:,6);
ST(:,2)=v(:,4)-v(:,7);
SE(:,1)=v(:,3)-v(:,12);
SE(:,2)=v(:,4)-v(:,13);

Dotproducts
[elb]=dotproduct(EW,ES);
[wri]=dotproduct(WF,WE);
[sho]=dotproduct(ST,SE);

Combine output angles
output=[sho',elb',wri'];

Dotproduct.m

function [angfilt]=dotproduct(A,B)
% This function calculates joint angles using the dot product
% Danielle Boucher
% June 18, 2012

% Determine vector lengths
[rows,cols]=size(A);

% Dot Prod 2D
for i=1:rows
    dotprod(i)=dot(A(i,:),B(i,:));
    maga=sqrt(A(i,1)^2+(A(i,2)^2));
    magb=sqrt(B(i,1)^2+(B(i,2)^2));
    a(i)=((acos(dotprod(i)/(maga*magb)))*180/pi);
end;

% Low pass 2nd order butterworth filter cutoff 30 Hz
[c,d]=butter(2,30/125,'low');
angfilt=(filtfilt(c,d,a));

Average.m

function [ANG_avg,maxes,min]=average(ANG_1,ANG_2,ANG_3)
% This program normalizes the 3 files to the same length, then averages
% joint angles for the 3 files, and determines max and min angle for each
% variable.
% Danielle Boucher
% Created April 22, 2012

clear index;

% Normalize all to length 1000
for i=1:3;
    for t=1:1000;
        eval(['index(t)=floor(((length(ANG_' num2str(i) '))*t)/1000);'])
        if index(t)==0;
            index(t)=1;
        end;
    end;
end;
%Label Columns
eval([{'shox': 'num2str(i) =ANG_.' num2str(i) ':,:,1;}])
eval([{'elbx': 'num2str(i) =ANG_.' num2str(i) ':,:,2;}])
eval([{'wrix': 'num2str(i) =ANG_.' num2str(i) ':,:,3;}])
eval([{'shoy': 'num2str(i) =ANG_.' num2str(i) ':,:,4;}])
eval([{'elby': 'num2str(i) =ANG_.' num2str(i) ':,:,5;}])
eval([{'wriy': 'num2str(i) =ANG_.' num2str(i) ':,:,6;}])
eval([{'shoz': 'num2str(i) =ANG_.' num2str(i) ':,:,7;}])
eval([{'elbz': 'num2str(i) =ANG_.' num2str(i) ':,:,8;}])
eval([{'wriz': 'num2str(i) =ANG_.' num2str(i) ':,:,9;}])

%Index columns
eval([{'shox': 'num2str(i) =shox' num2str(i) '(index);'}])
eval([{'elbx': 'num2str(i) =elbx' num2str(i) '(index);'}])
eval([{'wrix': 'num2str(i) =wrix' num2str(i) '(index);'}])
eval([{'shoy': 'num2str(i) =shoy' num2str(i) '(index);'}])
eval([{'elby': 'num2str(i) =elby' num2str(i) '(index);'}])
eval([{'wriy': 'num2str(i) =wriy' num2str(i) '(index);'}])
eval([{'shoz': 'num2str(i) =shoz' num2str(i) '(index);'}])
eval([{'elbz': 'num2str(i) =elbz' num2str(i) '(index);'}])
eval([{'wriz': 'num2str(i) =wriz' num2str(i) '(index);'}])
end

%Average each marker
shox_avg=(shox1+shox2+shox3)/3;
elbx_avg=(elbx1+elbx2+elbx3)/3;
wrix_avg=(wrix1+wrix2+wrix3)/3;
shoy_avg=(shoy1+shoy2+shoy3)/3;
elby_avg=(elby1+elby2+elby3)/3;
wriy_avg=(wriy1+wriy2+wriy3)/3;
shoz_avg=(shoz1+shoz2+shoz3)/3;
elbz_avg=(elbz1+elbz2+elbz3)/3;
wriz_avg=(wriz1+wriz2+wriz3)/3;

%maxes
maxshox=max(shox_avg);
maxelbx=max(elbx_avg);
maxwrix=max(wrix_avg);
maxshoy=max(shoy_avg);
maxelby=max(elby_avg);
maxwriy=max(wriy_avg);
maxshoz=max(shoz_avg);
maxelbz=max(elbz_avg);
maxwriz=max(wriz_avg);
maxes=[maxshox,maxelbx,maxwrix,maxshoy,maxelby,maxwriy,maxshoz,maxelbz,maxwriz];

%mins
minshox=min(shox_avg);
minelbx=min(elbx_avg);
\[
\text{minwrix} = \min(\text{wrix}_\text{avg}); \\
\text{minshoy} = \min(\text{shoy}_\text{avg}); \\
\text{minelby} = \min(\text{elby}_\text{avg}); \\
\text{minwriy} = \min(\text{wriy}_\text{avg}); \\
\text{minshoz} = \min(\text{shoz}_\text{avg}); \\
\text{minelbz} = \min(\text{elbz}_\text{avg}); \\
\text{minwriz} = \min(\text{wriz}_\text{avg});
\]

\[\text{mins} = \{\text{minshox}, \text{minelbx}, \text{minwrix}, \text{minshoy}, \text{minelby}, \text{minwriy}, \text{minshoz}, \text{minelbz}, \text{minwriz}\};\]

%Recombine
\[\text{ANG}_\text{avg} = \{\text{shox}_\text{avg}, \text{elbx}_\text{avg}, \text{wrix}_\text{avg}, \text{shoy}_\text{avg}, \text{elby}_\text{avg}, \text{wriy}_\text{avg}, \text{shoz}_\text{avg}, \text{elbz}_\text{avg}, \text{wriz}_\text{avg}\};\]