MUSCULOSKELETAL BIOMECHANICS OF HUMAN ROLLING

A Thesis by

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MUSCULOSKELETAL BIOMECHANICS OF HUMAN ROLLING

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Industrial and Manufacturing Engineering.

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DEDICATION

I dedicate this work to my Parents, Younger Brother, Wife, Uncles, Aunts, and Cousins.
ACKNOWLEDGMENTS

There were numerous people who have contributed in their own specific manner to the completion of my thesis, and I am thankful for their support. First, I would like to express my sincere gratitude to my advisor Dr. Nils Hakansson for the continuous support of my MS study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my MS study. I would also like to thank my family and friends for their support over the years. My heartfelt gratitude to committee members: Dr. Kim Cluff and Dr. Rob Manske. Special thanks goes to Dr. Michael Jorgensen and Dr. Lawrence Whitman. I am grateful to Linh Q. Vu for his help collecting the data.

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ABSTRACT

Rolling in the bed is an essential and complex activity of daily living. A reduction in rolling variability may reduce the complexity and aid our understanding of human rolling. The goal of this study was to find the mechanical energy requirements for rolling and calculate the musculature demands associated with rolling under two conditions: 1) arms crossed over the chest and 2) arms uncrossed and free to move naturally. The objectives of this study were investigated in two chapters.

The objectives of the first chapter were to calculate and compare the mechanical energy requirements for both whole body and individual body segments under the two rolling conditions. Kinematic data were recorded from healthy adults and analyzed to calculate the mechanical energy generated for each rolling condition. The mechanical energy for arms crossed was $60.1 \pm 12.1\text{J}$ and for arms uncrossed was $72.6 \pm 13.8\text{J}$ respectively. The statistical analysis indicated that there was a significant difference between two rolling conditions and the arms were the primary contributor for the observed energy differences.

The objectives of the second chapter were to determine and compare the muscle work generated by the whole-body and individual segments for each rolling condition. Kinematic and ground reaction force data were recorded and used to generate rolling simulations and calculate muscle work measures. The muscle work averaged across subjects for rolling with the arms crossed and uncrossed was $538.3 \pm 195.1\text{J}$ and $569.9 \pm 105.7\text{J}$ respectively. The statistical analysis indicated that there was no significant difference in overall muscle work between the two rolling conditions. In contrast, there was a significant difference in shoulder muscle work between rolling conditions.
PREFACE

The method chosen to present this research was to develop a set of independent chapters in manuscript format that are suitable for submission to peer-reviewed journals for publication. As a result of this method, some redundancy is present in the Introductions and Methods of the chapters. Chapter 2 has been published in the American Society of Biomechanics Conference and Biomedical Engineering Society Conference as follows:


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1. INTRODUCTION

1.1 Objectives

Rolling in the bed is a milestone in human development and a critical activity of our everyday life. It serves to increase comfort and prevent ischemic-associated injuries to the tissues, i.e., pressure ulcers. It is a challenging task for people with limited mobility who cannot roll and healthcare providers who assist people with limited mobility to roll. The inability to roll could contribute to the development of pressure ulcers and other medical complications. A better understanding of the basic principles of human rolling could help reduce the incidence of these conditions. Research on human movement, including balancing, reaching, walking, running, jumping and pedaling, has been investigated for hundreds of years. In contrast, research on human rolling has not been studied at the same level of detail as other movements.

Rolling is associated with a large number of variables. A reduction in rolling variability may improve our understanding of human rolling. Therefore, the first objectives of this study were to determine whether crossing the arms over the chest changed the energy demands of rolling from the supine to side-lying position, and to compare the energy contributions of individual body segments.

Human movement associated with factors including coordination of muscles and neural activities. Experimental techniques alone are unable to elucidate the complex muscle activities and neuromuscular control required for human movement. Musculoskeletal computer modeling is an effective means to gain additional insight into movement. Biomechanical investigators have used different types of musculoskeletal modeling techniques to describe the human motion. But, rolling motion has not been studied with computer models and simulation software. The muscle work
necessary for rolling are unknown and near impossible to acquire from experimental method alone. Computer modeling and simulation techniques can provide further insight into the muscle forces and activities necessary for rolling. To this end, the second objective of this study was to determine and compare the muscle work necessary for rolling with arms crossed and arms uncrossed for whole-body and individual body segments.

1.2 Research Overview

The mechanical energy requirements of whole-body and individual body segments for two rolling conditions was provided in Chapter 2. Chapter 2 describes how kinematic data were collected and incorporated into a biomechanics simulation software to calculate the COM, height of the COM, linear and angular velocities. The resultant kinematics were used to calculate the mechanical energy measures for each rolling condition. Multiple statistical analyses were performed to find the differences of mechanical energy between whole-body and individual segments for both rolling conditions.

Chapter 3 presents on a full-body model development and rolling simulation generation. The resultant inverse kinematics presented in Chapter 2 and the experimental ground reaction forces collected from force plates were imported into the simulation software to generate the rolling simulations. The resultant simulation was analyzed to calculate the muscle work measures for whole body and individual segments. To find the differences in muscle work measures for whole-body and individual body segments between two rolling conditions several statistical analyses were performed.
2. MECHANICAL ENERGY DIFFERENCES IN ARM-CONSTRAINED HUMAN ROLLING

2.1 Abstract

The ability to roll, most commonly executed as turning in bed, is a milestone in human development and is one of the most fundamental activities of daily living. People use a wide range of movement patterns when rolling from the supine to side-lying position. A reduction in rolling variability could facilitate a biomechanical analysis and improve our understanding of rolling. The objectives of this study were to i) determine whether crossing the arms over the chest changed the energy demands of rolling from the supine to side-lying position, and ii) compare the energy contributions of individual body segments. To fulfill these objectives, kinematic data were collected from 10 healthy subjects as they rolled from the supine to side-lying position. Marker position data were imported into OpenSim to calculate the kinematics of the whole body and individual body segments. The mechanical energy was comprised of two components 1) potential energy and 2) kinetic energy. Total energy was calculated by summing all positive increments in potential energy and kinetic energy. The mechanical energy averaged across subjects for rolling with the arms crossed and uncrossed was $60.1 \pm 12.1\text{J}$ and $72.6 \pm 13.8\text{J}$, respectively. The potential energy component comprised the majority of total energy for rolling both with the arms crossed (90%) and uncrossed (87%). The statistical analysis indicated that there was a significant difference between the total energy measures for rolling with the arms crossed and uncrossed. The mechanical energy of individual segments averaged across subjects for rolling with the arms crossed and uncrossed ranged from $1\text{J}$ to $30.7\text{J}$ and $2.5\text{J}$ to $28.3\text{J}$, respectively. The majority of the energy was contributed by the pelvis and torso segment for rolling with arms crossed (51%) and uncrossed (39%). There was a significant difference between the measures for rolling with the
arms crossed and uncrossed for two segments, right arm, and left arm. There was not enough
evidence to identify a significant difference for the right leg, left leg and pelvis and torso segments.

2.2 Introduction

Decubitus ulcers, most commonly known as pressure ulcers, are a serious problem for both patients
and health care providers [1]. Pressure ulcers lead to increased morbidity, pain and suffering, and
health care costs. Every year 1.7 million patients develop pressure ulcers in the United States [2].
In addition, annually $11 billion are spent on pressure ulcers treatment in US and similar high
costs are also noticed all over the world [1]. The treatment of a full-thick pressure ulcer requires
$70,000 [1]. More than 2.5 million patients suffer from pressure ulcers in acute-care facilities and
more than 60,000 people die as result of pressure ulcers annually [3]. Pressure ulcers are a
significant threat for the people who have limited mobility. Elderly people, more than 65 years,
develop 70% of the pressure ulcers [4]. Young people who have a neuromuscular disease or
mobility limitation are also susceptible to develop pressure ulcers.

Pressure ulcers are developed on underlying tissue due to prolonged pressure (i.e. body weight). It
can occur any place when people are subjected to sustained mechanical loads. Sustained load
reduces blood flow to that tissue area and renders the tissues ischemic. The greater the pressure
magnitude and duration on a tissue area, the greater the possibility that the tissue will be injured
and form a pressure ulcer. Tissue covering bony prominences, e.g., the back of the head, shoulders,
elbows, buttocks, and heels, are more susceptible to pressure ulcer formation. Takeshi, et al.
reported that pressure up to 70mmHg at the sacrum and 45mmHg are generated when a person lay
in the supine position [5]. Pressure ulcer formation can occur after an hour of total immobility. To
this end, frequent repositioning and rolling in the bed is one of the most important methods to
reduce the incidence of pressure ulcers [5].
The ability to roll, most commonly executed as turning in bed, is a milestone in human development [6] and is one of the most fundamental activities of daily living. Rolling requires coordinated motion of the trunk and upper and lower extremities [7]. People who cannot roll due to injury or disability are at greater risk of developing pressure ulcers and other medical complications. There is no reliable norm or standard to compare the rolling motion [8]. The underlying mechanisms, i.e., the neuromuscular coordination and muscular strength requirements, necessary to roll, remain unknown. Whereas research on various movement such as walking [9], running [10], balancing [11], reaching [12], jumping [13] and pedaling [14] have been performed extensively, studies on rolling motion are limited [8, 15-17].

People use a wide range of movement patterns when rolling from the supine to side-lying position. Richter et al. observed 32 different combination of three body regions (upper extremities, lower extremities and head and trunk) when subjects rolled from the supine to prone position [15]. Their results identified four primary movement patterns for the three body regions. Sekiya et al. performed kinematic and kinetic analyses on a constrained rolling motion of healthy adults [8]. They observed that the hip abduction-adduction angle remained constant throughout the rolling motion when one leg was used to push off the ground. They also noticed that the hip rotation angle was in the neutral or slightly internally rotated position at the beginning of the motion, and externally rotated toward the end of the rolling motion.

The motion of the upper extremities is a primary source of the variability in the movement patterns [7]. A reduction in rolling variability could facilitate a biomechanical analysis and improve our understanding of rolling. Therefore, the primary goal of the study was to determine whether constraining the arms would alter biomechanical measures associated with rolling. To this end, the first objective of this study was to determine whether crossing the arms over the chest changed the
energy demands of rolling from the supine to side-lying position. A second objective was to compare the energy contributions of individual body segments and identify the segments that contributed to the observed mechanical energy differences between the two rolling conditions.

2.3 Methods

2.3.1 Subjects

Written informed consent was obtained from 10 healthy subjects (male to female ratio 6:4) who volunteered for the study (Appendix A). The weight of the subjects ranged from 60 to 88 kg (mean 74 kg) (Appendix A). Subjects did not have any mobility limitations that would inhibit their ability to roll. The experimental protocol was approved by the Wichita State University Human Subjects Institutional Review Board.

2.3.2 Experimental Protocols

Kinematic data were collected from the subjects as they rolled from the supine to side-lying position using an 8-camera video based motion analysis system and Cortex v5.3 software (Motion Analysis Corp., Santa Rosa, CA). A modified Helen Hayes marker set (31 retro-reflective markers; Table 2.1) was used to define the foot, shank, thigh, pelvis, torso, upper and lower arms, and head segments of each subject for a standing static trial (Figure 2.1). For the static trial, subjects were instructed to stand facing forward in the anatomical position. The static trial was necessary to establish subject joint centers and define segment lengths for the development of a scaled biomechanical model. Rolling trials were collected using 22 retro-reflective markers (Figure 2.2, Table 2.1). All video motion capture data were recorded at 50 frames per second.

For the rolling trials, subjects laid on a firm surface in the supine position. A small pillow was positioned under the subjects’ head for comfort and to mimic their normal rolling motion environment. Subjects were then instructed to roll to their right into a side-lying position at a self-
selected speed. Subjects performed two rolling conditions: i) arms crossed over the chest and ii) arms uncrossed and free to move naturally. Each subject performed five rolling trials with their arms crossed followed by five trials with their arms uncrossed, resulting in 100 trials total.

Initiation and cessation of the rolling motion was based on the shoulder and pelvis angular velocities [18]. Initiation of the roll was defined as the earlier occurrence of the last peak before the shoulder or pelvis angular velocity increased monotonically towards its peak velocity. The latter of the shoulder or pelvis angular velocities to reach zero after achieving its peak velocity defined the cessation of the motion. Based on this definition of roll initiation and cessation (Appendix A), trials of different time lengths were normalized as a percentage of the rolling motion (supine to side-lying) and compared.

2.3.3 Data Processing

Marker position data were imported into OpenSim (v3.2) [19] to calculate the kinematics of the whole body and individual body segments. The parameters of a full body musculoskeletal model consisting of 20 segments and 37 degrees-of-freedom were scaled using the OpenSim Scale Model tool to best fit the experimentally measured subject mass and marker positions (Figure 2.3) [20]. The Inverse Kinematics tool was then used to calculate the limb segment positions and joint angles that reduced the difference between the experimental and virtual marker position data. The resultant kinematics were imported into Analyze tool to calculate centers of mass (COM) positions and linear (v) and angular (ω) velocities of each body segment. The resultant BodyKinematics were low-pass filtered at 4Hz using a zero-phase shift Butterworth digital filter using custom-written software algorithms (Appendix B).

The segment kinematics were used to calculate the potential and kinetic energy of the whole body and individual segments including right and left arms, pelvis and torso, and right and left legs. The
kinetic energy was comprised of two components: 1) translational energy, in which the energy is a function of linear velocity, and 2) rotational energy, in which the energy as a result of angular velocity. The potential \( E_p \) and kinetic \( E_k \) energy were calculated as:

\[
E_p = mgh
\]

\[
E_k = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2
\]

where \( m \) is the mass of body segment, \( g \) is the gravitational constant, \( h \) is the height of the segment COM, \( v \) is the linear velocity of the segment COM, \( I \) is the mass moment of inertia of the segments, and \( \omega \) is the angular velocity of the segment COM. Total energy \( E_{tot} \) was calculated by summing all positive increments \( (pos) \) in \( E_p \) and \( E_k \) [21] as follows:

\[
E_{tot} = \sum_{i=1}^{n} [pos(E_{p,i+1} - E_{p,i}) + pos(E_{k,i+1} - E_{k,i})]
\]

2.3.4 Statistical Analysis

To determine whether crossing the arms over the chest changed the energy demands of rolling from the supine to side-lying position for the body as a whole, a two-factor repeated measures ANOVA (\( \alpha = 0.05 \)) was performed to identify differences in \( E_{tot} \) between the two rolling conditions. The two factors were rolling condition at two levels and trials at five levels. To compare the energy contributions of individual body segments, five two-factor repeated measures ANOVAs (\( \alpha = 0.05/n \) where \( n \) is 5 for the Bonferroni correction) were performed to identify energy differences between the individual segments for the two rolling conditions. The two factors were rolling condition at two levels and trials at five levels.
2.4 Results

The mechanical energy averaged across subjects for rolling with the arms crossed and uncrossed was $60.1 \pm 12.1\text{J}$ and $72.6 \pm 13.8\text{J}$ (Table 2.2), respectively. For nine of the ten subjects, the mechanical energy averaged across the five trials was lower for rolling with the arms crossed than with the arms uncrossed (Figure 2.4). The averaged $E_p$ for rolling with arms crossed and uncrossed was $54.2 \pm 10.5\text{J}$ and $62.7 \pm 9.9\text{J}$ (Table 2.2), respectively. The $E_p$ component comprised the majority of $E_{tot}$ for rolling both with the arms crossed (90%) and uncrossed (87%) (Figure 2.4).

The $E_k$ averaged across subjects for rolling with the arms crossed and uncrossed was $5.9 \pm 2.5\text{J}$ and $9.8 \pm 5.7\text{J}$ (Table 2.2), respectively. The $E_k$ component contribution of $E_{tot}$ was 10% for arms crossed and 13% for arms uncrossed rolling. The translational energy component was the majority of $E_k$ for both rolling conditions. The averaged translational energy component of $E_k$ was 98% and the averaged rotational energy component of $E_k$ was only 2% for rolling with arms crossed. The averaged transitional energy component of $E_k$ was 99% and the averaged rotational energy component of $E_k$ was only 1% for rolling with arms uncrossed (Table 2.2). The statistical analysis indicated that there was a significant difference ($p = 0.007$) between the $E_{tot}$ measures for rolling with the arms crossed and uncrossed. There were no identified differences in $E_{tot}$ associated with the trials or the interaction between trials and rolling conditions.

The mechanical energy of individual segments averaged across subjects for rolling with the arms crossed and uncrossed ranged from 1J to 30.7J and 2.5J to 28.3J, respectively (Table 2.3). The pelvis and torso and left leg segments were the primary contributors to the observed mechanical energy. The majority of the energy was contributed by the pelvis and torso segment for rolling with arms crossed (51%) and uncrossed (39%) (Figure 2.5). The left leg contributed 34% of the total mechanical energy for rolling with arms crossed and 30% for rolling with arms uncrossed.
Both right and left arms and right leg contributions to the total mechanical energy for rolling with arms crossed were 2%, 7% and 6% respectively and for rolling with arms uncrossed were 3%, 21% and 7% respectively (Figure 2.5). There was a significant difference between the measures for rolling with the arms crossed and uncrossed for two segments, right arm ($p<0.001$), and left arm ($p<0.001$). There was not enough evidence to identify a significant difference for the right leg ($p=0.239$), left leg ($p=0.479$) and pelvis and torso ($p=0.094$).

2.5 Discussion

There are limited sources in the literature that present quantitative kinematic and kinetic data on human rolling. The existing literature focuses is on health care providers as they transfer patients rather than the mechanical demands of rolling oneself [22, 23]. To fill the void, this study provides normative kinetic data for rolling under two conditions. Where possible, comparisons to other rolling literature have been made to provide context for the data from this study.

Rolling is a complex movement that requires a coordinated motion of the entire body. The underlying musculoskeletal biomechanics have not been widely studied. Therefore, the objectives of this study were (i) to compare the mechanical energy requirements for arms crossed and arms uncrossed rolling and (ii) to compare the energy contribution of individual body segments under two different rolling conditions when subjects rolled from the supine to side-lying position. One key finding of this study was that rolling with the arms crossed was associated with less mechanical energy than rolling with the arms uncrossed. A second key finding was that increases in potential energy accounted for most of the mechanical energy generated to roll. A final key finding was that the majority of the energy differences between rolling conditions was associated with the arm segments. Before discussing the importance of these findings, several methodological issues should be reviewed to assess their potential to influence the results of the study.
2.5.1 Methodological Issues

One potential limitation relates to the surface upon which the subjects rolled. This surface was chosen as a means to provide a standard or norm. Each subject was accustomed to some form of mattress with a specific firmness. However, they all have had the experience of rolling on a firm surface. A second potential limitation relates to subject health and age. In this study, all the subjects were young and healthy. As such, the results from this study may not be representative of other populations. However, without an understanding of the basic musculoskeletal biomechanics of healthy rolling, it may not be possible to identify and address limitations associated with impaired rolling. The third potential limitation relates to the sample size. In this study, 10 subjects were recruited to perform the rolling trials. However, repeated trials for each subject and each condition were used to increase the power of the statistical analyses, reduce the chance of a Type II error, and provide greater confidence in the statistical outcomes. The fourth potential limitation relates to the rolling order. This order of rolling was chosen to have the subjects perform the novel rolling condition before the more familiar one in an attempt to minimize variability between rolling trials.

2.5.2 Importance/Interpretation of Results

The finding that rolling with the arms crossed was associated with less mechanical energy has important implications for both active and passive rolling. First, people who have compromised mobility and strength and may be at a “tipping point” with regards to their ability to roll may benefit from the reduced energy requirements associated with arms-crossed rolling. Second, the findings of this current study affirm prior research regarding healthcare providers who assist in rolling mobility-limited people. Research has indicated that health care professionals are at greater risk of developing low back injuries due to repositioning patients [23]. To minimize this risk, two patient repositioning techniques have been recommended: pulling and rolling the patient towards
oneself and pushing and rolling the patient away. Both the patient pulling and pushing techniques recommend crossing the patients arm over the chest when they are rolled [22]. These techniques are recommended because they reduce the loads on the healthcare provider’s lower back. For a given rolling motion, an increase in generated energy would correspond to an increase in force production. Because rolling with the arms crossed requires less mechanical energy, crossing the arms of a patient has the potential to reduce the force requirements of a healthcare provider to roll a patient. As less mechanical energy reduces the external force of the health care professional, it also reduces the internal force production.

The results from this study indicate that the majority of energy generated in rolling is in the form of potential energy associated with raising the body COM (Figure 2.5). According to Kafri COM shifted as subject rolled from supine to side-lying position [17]. Our study also indicated that the whole body COM rose when subject rolled. When subject laid on the surface, the COM of different body segments was lower. As the body rose from supine to side-lying position, the height of the COM increased. In this study, it was observed that most of the generated energy was applied to increase the potential energy of the body by raising the COM from a low height in the supine position to a higher one in the side-lying position. Both translational and rotational velocities were lower for both rolling conditions. Based on the result, potential energy is less in arms crossed rolling compare to arms uncrossed rolling. During arms crossed rolling both arms were placed over the chest. As subject started rolling, the arms position was higher and as the rolling continued the arms position went lower. On the other hand, arms were positioned at the side during arms uncrossed rolling. As subject started rolling, the arms position was lower and as the rolling continued the arms position went higher.
Kinetic energy is associated with both translational and rotational velocity. Kinetic energy is proportional to the square of the translational/rotational velocity. In this study, the kinetic energy associated with rolling was approximately 12% of the total energy generated to roll. The subjects were instructed to roll at their self-selected speed. Had the subjects rolled at a faster rate, they could have generated more kinetic energy and the kinetic energy would have comprised a greater percentage of the overall energy generated. Because the potential energy would likely have remained the same as it was associated with raising the body COM, a faster rolling rate would have increased the overall energy of rolling from the supine to side-lying position. As such, perhaps the subjects chose the rate at which they rolled as a means to minimize the total energy requirements to roll. While this was not a focus of this study, future work could explore the relationship between energy and rolling speed.

The arms were the primary contributors to the observed mechanical energy differences. Analysis of individual body segment contributions to the net mechanical energy generated in rolling indicated that the arms generated less mechanical energy when subjects rolled with their arms crossed. Furthermore, the summed mechanical energies of the trunk segments and legs were not significantly different for both arms crossed (55.1J) and uncrossed (54.6J) rolling conditions (Table 2.3). This finding indicates that the arms were responsible for the observed differences in the energy demands (13.0J) between the two rolling conditions. The observation that the energy generated by the leg segments and pelvis and torso segment did not change implies that their contribution to the rolling motion was similar for both conditions. Based on the results, crossing the arms over the chest changed the energy demands of rolling from the supine to side-lying position. Specifically, the motion of the arms increased both potential and kinetic energy as they were raised and maneuvered in rolling.
2.6 Conclusion

Rolling is a complicated motor task for which there exist many movement patterns. This study was one of the first to quantify biomechanical measures of human rolling and the first to examine the effects of constraining the arms on the mechanical energy generated in rolling. The result that crossing the arms over the chest reduced the energy demands of rolling could have implications for future biomechanical studies and clinical settings. Additionally, the mechanical energy contributions from the arms were significantly different for the two rolling conditions whereas the mechanical energy contributions from the leg segments and pelvis and torso segment were not. Constraining the arms has an effect on the energy generated by the whole body and the arm segments but does not appear to influence the energy generated by the leg segments and pelvis and torso segment.
Figure 2.1 Standing static pose trial of subject with markers on the forehead, shoulders, left clavicle, S1 sacrum vertebrae, pelvis, arms and legs.
Figure 2.2 Rolling trial of subject with markers on the forehead, shoulders, left clavicle, pelvis, arms and legs.
Figure 2.3 Musculoskeletal model of rolling for the arms crossed (upper figure) and arms uncrossed (lower figure) conditions.
Figure 2.4 Mean whole-body mechanical energy of the five trials for each subject rolling with the arms crossed and uncrossed. Error bars represent ± 1 standard deviation.
Figure 2.5 Mean mechanical energy of individual body segments for the five trials by the ten subjects when rolling with the arms crossed and uncrossed. Error bars represent ± 1 standard deviation and asterisks indicate significant differences.
Figure 2.6 Potential and kinetic energy for the five trials by the ten subjects when rolling with the arms crossed and uncrossed.
<table>
<thead>
<tr>
<th>Static Trial</th>
<th>Rolling Trial</th>
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<tbody>
<tr>
<td>Top Head</td>
<td>Top Head</td>
</tr>
<tr>
<td>Right Shoulder</td>
<td>Right Shoulder</td>
</tr>
<tr>
<td>Right Elbow</td>
<td>Right Elbow</td>
</tr>
<tr>
<td>Right Wrist</td>
<td>Right Wrist</td>
</tr>
<tr>
<td>Left Shoulder</td>
<td>Left Shoulder</td>
</tr>
<tr>
<td>Left Elbow</td>
<td>Left Elbow</td>
</tr>
<tr>
<td>Left Wrist</td>
<td>Left Wrist</td>
</tr>
<tr>
<td>Right Anterior superior iliac spine</td>
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<td>Left Anterior superior iliac spine</td>
</tr>
<tr>
<td>Right Thigh</td>
<td>Right Thigh</td>
</tr>
<tr>
<td>Right Shank</td>
<td>Right Shank</td>
</tr>
<tr>
<td>Right Toe Lateral</td>
<td>Right Toe Lateral</td>
</tr>
<tr>
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<td>Left Thigh</td>
</tr>
<tr>
<td>Left Knee Lateral</td>
<td>Left Knee Lateral</td>
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<tr>
<td>Left Shank</td>
<td>Left Shank</td>
</tr>
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<td>Left Ankle Lateral</td>
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<tr>
<td>Left Toe Medial</td>
<td>Left Toe Medial</td>
</tr>
<tr>
<td>Left Clavicle Offset</td>
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</tr>
<tr>
<td>Left Toe Lateral</td>
<td>Left Toe Lateral</td>
</tr>
<tr>
<td>R Knee Anterior</td>
<td>R Knee Anterior</td>
</tr>
<tr>
<td>Right Ankle Anterior</td>
<td>Right Ankle Anterior</td>
</tr>
<tr>
<td>Right Toe Medial</td>
<td>Right Toe Medial</td>
</tr>
<tr>
<td>Left Knee Medial</td>
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</tr>
<tr>
<td>Right Knee Lateral</td>
<td>Right Knee Lateral</td>
</tr>
<tr>
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</tr>
<tr>
<td>Right Ankle Medial</td>
<td>Right Ankle Medial</td>
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</tr>
<tr>
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<td>Right Ankle Lateral</td>
</tr>
<tr>
<td>S1 Sacrum</td>
<td>S1 Sacrum</td>
</tr>
<tr>
<td>Left Heel</td>
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</tr>
<tr>
<td>Right Heel</td>
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Table 2.2 Mean of mechanical energy for rolling with the arms crossed and arms uncrossed.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$E_p$ (J)</th>
<th>$\frac{1}{2}mv^2$ (J)</th>
<th>$\frac{1}{2}I\omega^2$ (J)</th>
<th>$E_{tot}$ (J)</th>
<th>$E_p$ (J)</th>
<th>$\frac{1}{2}mv^2$ (J)</th>
<th>$\frac{1}{2}I\omega^2$ (J)</th>
<th>$E_{tot}$ (J)</th>
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<tr>
<td>1</td>
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<td>4.0</td>
<td>0.1</td>
<td>60.1</td>
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<td>73.1</td>
<td>72.5</td>
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<tr>
<td>2</td>
<td>69.0</td>
<td>7.0</td>
<td>0.2</td>
<td>76.2</td>
<td>65.0</td>
<td>5.0</td>
<td>70.2</td>
<td>70.1</td>
</tr>
<tr>
<td>3</td>
<td>67.0</td>
<td>7.0</td>
<td>0.2</td>
<td>74.2</td>
<td>69.0</td>
<td>8.0</td>
<td>77.2</td>
<td>77.6</td>
</tr>
<tr>
<td>4</td>
<td>46.0</td>
<td>2.0</td>
<td>0.1</td>
<td>48.1</td>
<td>65.0</td>
<td>4.0</td>
<td>69.1</td>
<td>69.1</td>
</tr>
<tr>
<td>5</td>
<td>48.0</td>
<td>8.0</td>
<td>0.3</td>
<td>56.3</td>
<td>62.0</td>
<td>15.0</td>
<td>77.3</td>
<td>77.6</td>
</tr>
<tr>
<td>6</td>
<td>58.0</td>
<td>6.0</td>
<td>0.1</td>
<td>64.1</td>
<td>78.0</td>
<td>21.0</td>
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<td>99.5</td>
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<td>7</td>
<td>48.0</td>
<td>5.0</td>
<td>0.1</td>
<td>53.1</td>
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<td>7.0</td>
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<td>66.6</td>
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<tr>
<td>8</td>
<td>36.0</td>
<td>2.0</td>
<td>0.0</td>
<td>38.0</td>
<td>40.0</td>
<td>4.0</td>
<td>44.1</td>
<td>44.5</td>
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<tr>
<td>9</td>
<td>65.0</td>
<td>8.0</td>
<td>0.2</td>
<td>73.2</td>
<td>66.0</td>
<td>15.0</td>
<td>81.2</td>
<td>80.8</td>
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<td>10</td>
<td>50.0</td>
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<td>0.2</td>
<td>59.2</td>
<td>57.0</td>
<td>11.0</td>
<td>68.2</td>
<td>67.5</td>
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Table 2.3 Mean and standard deviation of mechanical energy for rolling with the arms crossed and uncrossed of individual body segments. Values in bold indicate a significant difference.

<table>
<thead>
<tr>
<th></th>
<th>Arms Crossed</th>
<th></th>
<th>Arms Uncrossed</th>
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<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
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<tr>
<td>Right Leg</td>
<td>3.9</td>
<td>1.6</td>
<td>4.7</td>
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<td>Left Leg</td>
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</tr>
<tr>
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<td>0.4</td>
<td>2.5</td>
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<tr>
<td>Pelvis and Torso</td>
<td>30.7</td>
<td>6.9</td>
<td>28.3</td>
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</table>
3. MUSCLE WORK DIFFERENCES IN ARM-CONSTRAINED HUMAN ROLLING

3.1 Abstract

A growing problem for both elderly and mobility limited people is the frequent occurrence of pressure ulcers. Pressure ulcers are painful and can lead to increases in mortality as well as health care costs. Rolling in bed is an effective means to reduce the pressure ulcers and an important activity of daily living associated with quality of life. Muscle activity and the associated forces during rolling are unknown and near impossible to estimate from experimental methods alone. Computer-based musculoskeletal modeling and simulation techniques can provide additional insight into muscle measures. To this end, the objectives of this study were to generate a rolling simulation using musculoskeletal biomechanics simulation software to estimate muscle work associated with the two rolling conditions and estimate and compare the muscle work associated with individual segments for the two rolling conditions. To fulfill these objectives, kinematic, and kinetic data were collected from healthy college-aged subjects as they rolled from the supine to side-lying position. Marker position and ground reaction force data were imported into OpenSim to generate the rolling simulations. The simulation calculated muscle powers were analyzed to determine the muscle work. Muscle work was calculated by the time integral of the muscle power. Multiple statistical analyses were performed to find the difference in the muscle work between rolling with the arms crossed and uncrossed for both the whole-body and individual segments. The muscle work averaged across subjects for rolling with the arms crossed and uncrossed was 538.3 ± 195.1J and 569.9 ± 105.7J, respectively. The statistical analysis indicated that there was no significant difference between the total muscle work measures for rolling with the arms crossed and uncrossed. The lower extremities and pelvis muscles contributed 383.5.8± 135.0J and 384.5 ± 83.6J of total muscle work for arms crossed and arms uncrossed rolling, respectively. The upper
extremities and torso muscles contributed 154.8 ± 72.3J and 185.3 ± 31.2J, respectively, to rolling with arms crossed and arms uncrossed. The torso and pelvis muscles contributed 104.8 ± 48.1J (Table 3.1) and 93.1 ± 21.3J to arms crossed and arms uncrossed rolling, respectively. The averaged muscles work without shoulder muscles was 485.8 ± 171.7 and 475.2 ± 93.3 respectively for rolling with arms crossed and arms uncrossed. The muscle work averaged for rolling with arms crossed and arms uncrossed was 52.5 ± 28.3J and 94.6 ± 26.7J, respectively, for shoulder muscles. There was no significant interaction between the upper extremities and torso muscles ($p = 0.231$), lower extremities and pelvis muscles ($p = 0.981$), torso and pelvis muscles ($p = 0.428$), and all muscles excluding shoulder muscles ($p = 0.847$) for rolling with arms crossed and arms uncrossed whereas the shoulder muscles ($p = 0.006$) did have a significant effect on rolling conditions.

3.2 Introduction

A growing problem for both elderly and mobility limited people is the frequent occurrence of pressure ulcers. From 1993 to 2006, the number of reported pressure ulcers in the United States increased by 80% [24]. Seventy percent of pressure ulcers are developed by elderly people aged more than 65 years old [4]. Young individuals who have mobility limitations also have an increased probability of developing pressure ulcers.

Pressure ulcers are painful and can lead to increases in mortality as well as health care costs. In 1990, the rate of mortality of hospitalized Medicare patients with pressure ulcers was 16.2% [2]. In 1987, hospitals spent approximately $215 million to treat pressure ulcer treatments [25]. In addition, in the United States, approximately $11 billion are spent annually on pressure ulcers [1].

Pressure ulcers can develop due to prolonged pressure on the underlying tissue. A pressure ulcer can develop in as little as one hour of immobility [5]. Prevention is much more effective than cure for pressure ulcers. It is very important to turn people, who cannot turnover on the bed, at least
every two hours to prevent pressure ulcers [4]. Rolling or turning on the bed not only helps to reduce pressure ulcer development but also provides comfort and improved sleep quality. Additionally, rolling in bed is an effective means to reduce the pressure ulcers and an important activity of daily living associated with quality of life.

Rolling is an activity that people perform on a daily basis without knowing. Rolling is one of the basic activities of our everyday life. Whereas other activities of daily living have been researched both theoretically and experimentally, for example balancing [11], reaching [12], walking [9], running [10], jumping [13], and pedaling [14], human rolling has received a little attention. It requires coordinated motion of the trunk and upper and lower extremities [7], however, underlying principles, i.e., the neuromuscular coordination and muscular strength requirements, necessary to roll have not been examined.

There are multiple ways by which people roll. According to Richter et al., healthy individuals exhibited a variety of movement patterns when they rolled from the supine to side-lying positions [15]. In their study, they identified 32 movement pattern combinations between the upper extremities, lower extremities, and head and trunk segments. Imposing constraints on the rolling motion could reduce the variability and number of movement pattern combinations. Sekiya et al. performed a study of a prescribed rolling motion in which subjects crossed their arms over their chest and used their right leg to push off the floor and initiate the roll. They observed that the hip abduction-adduction angle for the leg used to push off the ground remained constant throughout the rolling motion. They also noticed that the hip rotation angle was in the neutral or slightly internally rotated position at the beginning of the motion, and externally rotated toward the end of the rolling motion [8]. Vu et al. performed a kinematic analysis on human rolling motion under two conditions 1) arms crossed over the chest and 2) arms uncrossed and free to move naturally
The results of their study indicated that rolling with the arms crossed or uncrossed did not influence whether the shoulder or pelvis initiated the roll or whether shoulder or pelvis concluded the roll.

Movement science relies on observation; however, observation alone is insufficient to describe the mechanics of human motion [26]. Human motion requires the coordination of muscles and neural activities. Musculoskeletal modeling has proven to be a powerful tool for estimating muscle forces and neuromuscular activities associated with human motion that is too complicated to acquire from experimental approaches alone. For these reasons, biomechanical investigators have used different types of musculoskeletal modeling techniques, for example inverse kinematics [27], inverse dynamics [28], computed muscle control [29], and forward dynamics [30, 31], to describe the human motion. However, to date human rolling has not been studied using computer models and simulation software. Muscle activity and the associated forces during rolling are unknown and near impossible to estimate from experimental methods alone. Computer-based musculoskeletal modeling and simulation techniques can provide additional insight into muscle measures. Therefore, the first objective of this study was to generate a rolling simulation using musculoskeletal biomechanics simulation software to estimate muscle work associated with the two rolling conditions.

A reduction in rolling variability could facilitate biomechanical analyses that improve our understanding of rolling and the circumstances that inhibit a person’s ability to roll. Vu et al. found that rolling kinematics did not vary as a result of constraining the arms [18]. A follow-up study by Hassan et al. determined that rolling with one’s arms crossed over the chest requires less mechanical energy than rolling with the arms free to move naturally [32]. An analysis of the mechanical energy generated in individual segments during arm-constrained human rolling
indicated that the arms were the source of the observed energy differences. The analysis also indicated that there was no significant difference in the energy measures for the other segments including trunk (pelvis and torso), left and right legs [33]. These findings suggest that there may be differences in the muscle activities associated with the two rolling conditions. Additionally, muscular demand measures may provide insight into the factors that limit a person’s ability to roll. Therefore, the second objective of this study was to estimate and compare the muscle work associated with individual segments for the two rolling conditions.

3.3 Methods

3.3.1 Subjects

Written informed consent was obtained from 10 healthy subjects (male to female ratio 6:4) who volunteered for the study (Appendix A). The weight of the subjects ranged from 60 to 88 kg (mean 74kg) (Appendix A). Subjects did not have any mobility limitations that would affect their ability to roll. The experimental protocol was approved by the Wichita State University Human Subjects Institutional Review Board.

3.3.2 Experimental Protocols

Kinematic, kinetic, and electromyographic (EMG) data were collected from healthy college-aged subjects as they rolled from the supine to side-lying position. Kinetic data (ground reaction forces) were collected from four force plates arranged linearly along the length of the subject. EMG data were collected using surface electrodes from fifteen superficial muscles: right and left gluteus maximus, right and left gluteus medius, right and left rectus abdominis, right and left external oblique, right and left pectoralis major, left sternocleomastoid, left tibialis anterior, left biceps femoris, left gastrocnemius, and left quadriceps femoris. Subjects were instructed to lie in the supine position such that their head, torso, pelvis and heels rested on individual force plates. During
the experiment subjects dressed in tight clothing to help identify bony landmarks. For the static trial, subjects were instructed to stand stationary in the anatomical position. For the rolling trials, subjects laid on a firm surface in the supine position. A pillow was provided underneath of the subjects’ head to make their rolling motion natural. Subjects were instructed to roll to their right into a side-lying position at a self-selected speed. Subjects performed two types of rolling movements: i) arms crossed over the chest and ii) arms uncrossed and free to move naturally. Subjects performed five rolling trials with their arms crossed followed by five trials with their arms uncrossed. The third rolling trial from each rolling condition was used to generate the simulation.

3.3.3 Equipment

Kinematic data were collected using an 8-camera video based motion analysis system and Cortex v5.3 software (Motion Analysis Corp., Santa Rosa, CA). A modified Helen Hayes marker set (31 retro-reflective markers) was used to define the foot, shank, thigh, pelvis, torso, upper and lower arms, and head segments for each subject for the standing static pose. Rolling motion was collected using 22 retro reflective markers. Data were recorded 50 frames per second.

3.3.4 Modeling and Simulation

The rolling simulations were generated using a musculoskeletal biomechanics simulation software (OpenSim v 3.2) [19]. A full body model consisting of 20 segments, 37 degrees-of-freedom and 132 muscles was developed from three existing musculoskeletal models (Figure 3.1). The lower extremities and pelvis consisted of 78 muscles and upper extremities and torso consisted of 54 muscles. A total of 84 muscles (78 lower extremities including pelvis and 6 torso muscles) were added from an existing full body model [20]. The upper extremity and torso muscles were added from two existing models. Upper extremities including deltoid, supraspinatus, infraspinatus, teres minor, teres major, pectoralis major, coracobrachialis and triceps brachii (lateral head) muscle
groups were added from existing upper and lower body model [34]. Latissimus dorsi muscles were added from a lumbar spine model [35]. Two ellipsoid wraps were created in the torso case to specify the muscles path (Appendix C).

Marker position data were imported into OpenSim to generate the rolling simulations. The parameters of a full body musculoskeletal model were scaled using the OpenSim Scale Model tool to best fit the experimentally measured subject mass and marker positions [20]. The Inverse Kinematics tool was then used to calculate the limb segment positions and joint angles that reduced the difference between the experimental and virtual marker position data. The resultant kinematics and experimentally measured ground reaction forces were imported into the Computed Muscle Control (CMC) tool to calculate the muscle activations and lengths and the associated muscles forces and powers (Figure 3.2) for both experimental rolling conditions.

3.3.5 Method to Define the Beginning and End of a Roll

Initiation and cessation of the rolling motion was based on the shoulder and pelvis angular velocities [18]. Initiation of the roll was defined as the earlier occurrence of the last peak before the shoulder or pelvis angular velocity increased monotonically towards its peak velocity. The latter of the shoulder or pelvis angular velocities to reach zero after achieving its peak velocity defined the cessation of the motion. Based on this definition of roll initiation and cessation (Appendix A), trials of different time lengths were normalized as a percentage of the rolling motion (supine to side-lying) and compared.

3.3.6 Data Analysis

Both the raw sampled EMG and muscle activation data were filtered using a zero phase lag sixth-order Butterworth digital filter with 6 Hz cutoff frequency and normalized to the highest value measured for the respective muscle while rolling (Appendix D). The mean and the standard
deviation were calculated from the EMG from all subjects and compared the corresponding muscle activations calculated by the CMC tool (Appendix E). The simulation calculated muscle power was analyzed to determine the muscle work. Muscle work was calculated by the time integral of the muscle power [36]. Total muscle work generated to roll was calculated by summing all positive increments in muscle power [21]. A paired t-test ($\alpha = 0.05$) was performed to identify the differences in muscle work between two rolling conditions for whole-body. Five paired t-tests ($\alpha = 0.05/n$ where $n = 5$) were performed to test for differences in the muscle work between rolling with the arms crossed and uncrossed for five muscle groupings: i) the upper extremities and torso, ii) lower extremities and pelvis, iii) torso and pelvis, iv) shoulder muscles, and v) whole body muscles excluding the shoulder muscles between the two rolling conditions. To reduce the probability of type-I error, a Bonferroni correction was applied. The independent variables were the two rolling conditions (arms crossed over the chest and arms uncrossed and free to move naturally) and the dependent variable was muscle work.

3.4 Results
The EMG and CMC activations for rolling with the arms crossed and uncrossed were qualitatively similar for most of the muscles studied (Appendix E). The muscle work averaged across subjects for rolling with the arms crossed and uncrossed was $538.3 \pm 195.1 \text{J}$ (Table 3.1) and $569.9 \pm 105.7 \text{J}$ (Table 3.2), respectively. For five of the ten subjects, the averaged muscle work was lower for rolling with the arms crossed (Figure 3.3). The statistical analysis indicated that there was no significant difference ($p = 0.605$) between the total muscle work measures for rolling with the arms crossed and uncrossed.

The lower extremities and pelvis muscles contributed $383.5.8 \pm 135.0 \text{J}$ and $384.5 \pm 83.6 \text{J}$ (Figure 3.4) of total muscle work for arms crossed and arms uncrossed rolling, respectively. The upper extremities and torso muscle groups including external oblique, internal oblique, erector spinae,
deltoid, supraspinatus, infraspinatus, teres minor, teres major, pectoralis major, coracobrachialis, triceps brachii (lateral head), and latissimus dorsi contributed 154.8 ± 72.3J (Table 3.1) and 185.3 ± 31.2J (Table 3.2), respectively, to rolling with arms crossed and arms uncrossed. The torso and pelvis muscles comprising external oblique, internal oblique, erector spinae, and latissimus dorsi contributed 104.8 ± 48.1J (Table 3.1) and 93.1 ± 21.3J (Table 3.2) to arms crossed and arms uncrossed rolling, respectively. The averaged muscles work without shoulder muscles was 485.8 ± 171.7 (Table 3.1) and 475.2 ± 93.3 (Table 3.2) respectively for rolling with arms crossed and arms uncrossed. There was no significant interaction between the upper extremities and torso muscles ($p = 0.231$), lower extremities and pelvis muscles ($p = 0.981$), torso and pelvis muscles ($p = 0.428$), and all muscles excluding shoulder muscles ($p = 0.847$) for rolling with arms crossed and arms uncrossed. The muscle work averaged for rolling with arms crossed and arms uncrossed was 52.5 ± 28.3J (Table 3.1) and 94.6 ± 26.7J (Table 3.2), respectively, for shoulder muscles (deltoid, supraspinatus, infraspinatus, teres minor, teres major, pectoralis major, coracobrachialis, triceps brachii (lateral head), and latissimus dorsi). The shoulder muscles did have a significant effect on rolling conditions ($p = 0.006$).

The lower extremities and pelvis muscles performed the majority of muscle work for rolling with the arms crossed (71.2%) and uncrossed (67.5%). The contributions of the upper extremities and torso muscles to the total muscle work was lower than that of the lower extremities and pelvis muscles. The upper extremities and torso muscles contributed 28.8% and 32.5% of the total muscle work for rolling with arms crossed and arms uncrossed, respectively. The torso and pelvis muscles generated 19.5% and 16.3% of the total muscle work for rolling with arms crossed and uncrossed, respectively. The work performed by the shoulder muscles was 9.8% and 16.6% for arms crossed and uncrossed rolling, respectively.
3.5 Discussion

Rolling is a basic activity of daily living that requires the coordinated motion of the entire body. The basic mechanism of rolling has received little attention. The existing literature has focused on qualitative measures of human rolling. The muscle work required for rolling has not been studied. The first objective of this study was to develop rolling simulations and verify the simulation using a three-dimensional musculoskeletal full body model. The second objective was to investigate the contribution of upper extremities and torso, lower extremities and pelvis, torso and pelvis, shoulder and all muscles excluding shoulder muscles and compare the musculature demands under two rolling conditions. There were several noteworthy results from this study. First, whole body musculature work measures of human rolling for the two conditions were not significantly different. Second, a significant difference was observed between the work measures for the muscles that cross the shoulder when rolling with arms crossed and arms uncrossed. Third, for five of the ten subjects, the averaged muscle work measure was lower for rolling with the arms crossed than with the arms uncrossed. Prior to addressing the importance of these findings, a discussion of the underlying assumptions and limitations of the model is warranted.

3.5.1 Methodological Issues

One potential limitation is the number of muscles on the model. In this study 132 muscles were used on the model. Most humans have approximately 640 skeletal muscles. Therefore, the results of this study may not account for some of the muscle forces and interactions that exist in a real human body. However, the model used in this study was the same for both rolling conditions, so the effect of the reduced number of muscles on the results should be similar. Furthermore, the general agreement in the experimental EMG, an independent measure, with the CMC activation patterns provides confidence in the simulation results. The second potential limitation relates to
the muscle properties, such as fiber types, muscle cross-sectional area, and muscle velocities. Every effort was made to represent the experimental subjects with respect to modeling parameters, however, it was not possible to obtain exact muscle and anthropometric measures for the computer models. Because the computer models were used in a comparative study in which the subjects served as their own controls, the effects of the muscle and anthropometric measures would have influenced the results in a systemic manner. The third potential limitation relates to the sample size. In this study, 10 subjects were recruited to perform the rolling trials. Because there are no known studies on the muscle work associated with rolling, it was not possible to perform a power analysis to determine subject sample size \textit{a priori}. Given the complexity of the model development, the time required to generate the simulations, and subject sample sizes in other studies of similar design [37-39], the ten subjects recruited for this study was deemed adequate.

3.5.2 Importance/Interpretation of Results

Whole body muscle work measures of human rolling for the two rolling conditions were not significantly different. The whole body muscle work averages generated in the current study through musculoskeletal simulations differ from the whole body mechanical energy averages observed previously [32]. The muscle work calculated for rolling in this study ranged from 538.3 to 569.9 J. The whole body mechanical energy calculated for rolling in the previous study ranged from 60.1 to 72.6J. From the whole body mechanical energy study, it was observed that the majority of mechanical energy generated for rolling was associated with an increase in potential energy of the body. That is, most of the energy generated was used to raise the body COM from a lower energy supine position to a higher energy side-lying position. The high muscle work values calculated in this study indicates that much of the muscle work generated was not directly associated with the rolling motion. Unlike the mechanical energy analysis in which the calculated
potential energy represented the near minimum energy requirement to reposition from the supine to side-lying position, the muscle work does not. Much of the muscle work generated may have been associated with moving or positioning body segments in ways that did not contribute directly to rolling, for example to move the lower limbs in the horizontal plane. Whereas these motions would contribute to the kinetic energy generated (these contributions were small due to the low velocities), the muscle work may have been large due to the mass and inertia of the segments.

The averaged muscle work for the upper extremities and torso muscles, lower extremities and pelvis muscles, torso and pelvis muscles, and all muscles excluding the shoulder muscles ranged from 383.5 to 384.5 J, 154.8 to 185.3 J, 93.1 to 104.8 J, and 475.2 to 485.8 J, respectively. This study observed that there was no significant difference between individual segmental muscles except the shoulder muscles for the two rolling conditions. The findings of this study were reflective of the individual segmental mechanical energy measure observed previously [33]. In addition, the mean muscle work generated by the shoulder muscles was significantly different for the two rolling conditions. This finding is consistent with our previous study in which a significant difference was found between the mechanical energy measures for the upper extremities [33].

An interesting pattern of muscle work emerged from the averaged muscle work data. Five of the ten subjects generated more muscle work to roll with arms crossed than with the arms uncrossed. The five subjects who generated more work with the arms crossed, also generated more muscle work in the lower extremity and pelvis (ii) and torso and pelvis (iii) muscle groupings for rolling with the arms crossed (Table 3.1). The five subjects who generated more work with the arms uncrossed also generated more muscle work with the upper extremity and torso (i), lower extremity and pelvis (ii), and shoulder (iv) muscle groupings when rolling with the arms uncrossed (Table 3.2). These patterns suggest that there are two distinct rolling strategies, one torso-centric and one
extremity-centric. The subjects who generated more work with their arms crossed also generated more work with the muscles responsible for moving the torso and lower half of the body. In contrast, the subjects who generated more work with their arms uncrossed generated more work with all the muscles except those associated with the torso. Crossing the arms over the chest may promote torso-centric approaches due to the availability of being upper extremities to contribute to the rolling motion. As such, individuals who do not have upper extremity strength may need to rely more heavily on their torso muscles than those individuals who do have full utilization of their upper extremities.

3.6 Conclusion

Rolling is the most important activities of our daily living. It serves to increase comfort and prevent ischemic-associated injuries to the tissues, i.e., pressure ulcers. This study was one of the first to quantify musculature measures of human rolling under two rolling conditions 1) arms crossed and 2) arms uncrossed and free to move naturally. The results of this study identified that constraining the arms did not change the whole-body muscle work. Additionally, the muscle work contributions from the shoulders were significantly different for the two rolling conditions, whereas the muscle work contributions from the lower extremities and pelvis and torso muscle groupings were not.
Figure 3.1 A full body model consisting of 20 segments, 37 degrees-of-freedom and 132 muscles.
Figure 3.2 Rolling simulation for the arms crossed (upper figure) and arms uncrossed (lower figure) conditions using CMC tool.
Figure 3.3 Mean whole-body muscle work for each subject rolling with the arms crossed and uncrossed.
Figure 3.4 Mean muscle work of individual body segments for the ten subjects when rolling with the arms crossed and uncrossed. Error bars represent ± 1 standard deviation and asterisks indicate significant differences.
Table 3.1 Mean muscles work for rolling with arms crossed

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Table 3.2 Mean muscles work for rolling with arms uncrossed

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4. CONCLUSION

4.1 Summary

The purpose of this study were to determine whether constraining the arms would change the biomechanical measures associated with rolling. To this end, the objectives of this study were i) to determine the mechanical energy requirements necessary for rolling under two conditions 1) arms crossed and 2) arms uncrossed and free to move naturally, ii) to compare the total energy contribution of individual body segments for rolling with two conditions, iii) to determine the musculature demands necessary for both arms crossed and arms uncrossed rolling conditions, and iv) to compare the individual segment’s musculature demand between two rolling conditions. The main findings of this study are summarized as follows:

1. Rolling with the arms crossed was associated with less mechanical energy than rolling with the arms uncrossed.
2. The potential energy comprised most of the total mechanical energy to generate the rolling.
3. Both left and right arms were the primary contributor to the observed mechanical energy differences. Pelvis and torso segment contributed most of the energy. Left and right leg and pelvis and torso segments were not significantly different between the two rolling conditions.
4. The musculature demands of whole-body necessary for rolling with arms crossed and uncrossed were not significantly different.
5. There was a significant difference of the shoulder muscles between the two rolling conditions.
6. The averaged muscle work measure was lower for rolling with arms crossed and arms uncrossed for five of the ten subjects.

4.2 Methodological Issues

There were several limitations associated with this study. The limitations of this study are summarized as follows:

1. One potential limitation relates to the surface upon which the subjects rolled. This surface was chosen as a means to provide a standard or norm. Each subject was accustomed to some form of mattress with a specific firmness. However, they all have had the experience of rolling on a firm surface.

2. A second potential limitation relates to subject health and age. In this study, all the subjects were young and healthy. As such, the results from this study may not be representative of other populations. However, without an understanding of the basic musculoskeletal biomechanics of rolling, it may not be possible to identify and address limitations associated with impaired rolling.

3. The third limitation is the number of muscles on the model. In this study 132 muscles were used on the model. A real human body consists of 640 skeletal muscles. Therefore, the results of this study may not be a true representation of a real human body. However, the model used in this study may have the same systematic errors for both conditions. Therefore, the results are comparable between two conditions.

4. The fourth potential limitation relates to the muscle properties, such as fiber types, muscle cross-sectional area, muscle shortening and lengthening. Every effort was made to represent the experimental subjects with respect to modeling parameters. However, it was not possible to obtain exact muscle and anthropometric measures.
from computer modeling. It is impossible to use the realistic muscles properties in the muscle model. In addition, different people have different musculature properties. However, the focus of this study was to compare two different rolling conditions not to identify the absolute measures. The error of this study was systematic not random for both conditions. Therefore, the results of this study are comparable.
REFERENCES
REFERENCES


### A. ROLLING INITIATION AND CESSATION TIME, SEX AND WEIGHT FOR 10 SUBJECTS

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<td></td>
<td>0.84</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.28</td>
<td>6.28</td>
<td></td>
<td>1.12</td>
<td>5.42</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.08</td>
<td>5.78</td>
<td></td>
<td>2.5</td>
<td>6.04</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.98</td>
<td>5.56</td>
<td></td>
<td>1.46</td>
<td>5.68</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.84</td>
<td>6.12</td>
<td></td>
<td>1.72</td>
<td>5.28</td>
<td></td>
</tr>
</tbody>
</table>
### Subject 9, Male, 83.91 kg

<table>
<thead>
<tr>
<th>Trial</th>
<th>Arms Crossed</th>
<th>Arm Uncrossed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start time</td>
<td>End time</td>
</tr>
<tr>
<td>1</td>
<td>1.86</td>
<td>4.76</td>
</tr>
<tr>
<td>2</td>
<td>1.64</td>
<td>4.52</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>4.44</td>
</tr>
<tr>
<td>4</td>
<td>1.56</td>
<td>4.62</td>
</tr>
<tr>
<td>5</td>
<td>1.46</td>
<td>3.84</td>
</tr>
</tbody>
</table>

### Subject 10, Female, 67.59 kg

<table>
<thead>
<tr>
<th>Trial</th>
<th>Arms Crossed</th>
<th>Arm Uncrossed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start time</td>
<td>End time</td>
</tr>
<tr>
<td>1</td>
<td>1.24</td>
<td>4.64</td>
</tr>
<tr>
<td>2</td>
<td>1.32</td>
<td>3.86</td>
</tr>
<tr>
<td>3</td>
<td>1.24</td>
<td>4.42</td>
</tr>
<tr>
<td>4</td>
<td>1.26</td>
<td>3.78</td>
</tr>
<tr>
<td>5</td>
<td>1.66</td>
<td>3.9</td>
</tr>
</tbody>
</table>
B. MATLAB PROGRAMS FOR MECHANICAL ENERGY CALCULATION

MATLAB Program B1

% code to read in rolling subject COM position and velocity data
% as well as filter the data, interpolate the data to percent start to
% end time, and calculate positive increments in kinetic and potential
% energies

% Change in _v2 - multiplies angular velocity about all three axes

function [energy] = rolling_MME_calc(froot, IT1, IT2, crossed, mass, time)

% condition to see if using arms crossed or uncrossed trials
if crossed
    % read in arms crossed position and velocity data to position data matrix
    pos_data = open_matrix([froot, 'Subject', int2str(IT1), '_trial', int2str(IT2), '_BodyKinematics_pos_global.sto']);
    vel_data = open_matrix([froot, 'Subject', int2str(IT1), '_trial', int2str(IT2), '_BodyKinematics_vel_global.sto']);
else
    % read in arms crossed position and velocity data to position data matrix
    pos_data = open_matrix([froot, 'Subject', int2str(IT1), '_trial', int2str(IT2), 'un_BodyKinematics_pos_global.sto']);
end
vel_data = open_matrix([froot, 'Subject', int2str(IT1), '_trial', int2str(IT2), 'un_BodyKinematics_vel_global.sto']);
end

% determine size of position data matrix
[rp, cp] = size(pos_data);

% determine size of velocity data matrix
[rv, cv] = size(vel_data);

% determine size of mass data matrix
[rm, cm] = size(mass);

%% Filtering

% Nyquist frequency
Wn = 50/2;
cutoff = 4;  % cutoff frequency

% Generate filter coefficients
[B, A] = butter(6, cutoff/Wn);

% filter data
p_data = [pos_data(:,1), filtfilt(B, A, pos_data(:,2:cp))];
v_data = [vel_data(:,1), filtfilt(B, A, vel_data(:,2:cp))];

%% Rolling Time Window data
% time set for trial [arms crossed (start end) & uncrossed (start end)]

if crossed
    tstart = find(pos_data(:,1) == time(1,1));
    tend = find(pos_data(:,1) == time(1,2));
else
    tstart = find(pos_data(:,1) == time(1,3));
    tend = find(pos_data(:,1) == time(1,4));
end

%% Select Relevant Data
% select y-coordinate position data in rolling time window tstart:tend
pos_y1 = p_data(tstart:tend,9:6:cp-3); % CP-3 to omit whole body COM, just CP to include CoM

% loop to select columns of linear velocity data in rolling time window tstart:tend
% start at row 8 to skip ground values
% includes whole body COM, use following to omit whole body COM
% for IT1 = 1:((cv-1)/3-1)/2-1  <-- omit whole body COM
for IT1 = 1:((cv-1)/3-1)/2-1
    l_vel_sqd1(:,IT1) = sum((v_data(tstart:tend,6*IT1+2:6*IT1+4).^2),2);
    a_vel_sqd1(:,(3*IT1-2):(3*IT1)) = ((v_data(tstart:tend,6*IT1+5:6*IT1+7)*pi/180).^2);
end
%% Interpolated Rolling data 0-100 percent

% % interpolate data to percentage of roll based on start and end times
% % on analysis worksheets

x1 = (pos_data(tstart,1):((pos_data(tend,1) - pos_data(tstart,1))/79):pos_data(tend))';
pos_y = interp1(pos_data(tstart:tend,1),pos_y1,x1);
l_vel_sqd = interp1(pos_data(tstart:tend,1),l_vel_sqd1,x1);
a_vel_sqd = interp1(pos_data(tstart:tend,1),a_vel_sqd1,x1);

%% Mass and Inertia Diagnol Matrices

% Mass diagnol matrix
mass_matrix = diag(mass(:,1));

% Inertia diagnol matrix
I_matrix =  diag(reshape(mass(:,2:4)',[60,1]));

%% Energy Calculations

% per trial ... energy = mgh + 1/2mv^2 + 1/2w^2

mgh = 9.81 * pos_y * mass_matrix;
ke_lin = 0.5 * l_vel_sqd * mass_matrix;
ke_ang1 = 0.5 * a_vel_sqd * I_matrix;
% Angular Velocity Element

% a_vel_all contains three ang velocities for each segment. Need to sum
% them 3 columns at a time

for IT1 = 1:20
    ke_ang(:,IT1) = sum(ke_ang1(:,3*IT1-2:IT1),2);
    mgh(:,IT1) = mass(IT1,1) * 9.81 * pos_y(:,IT1);
    ke_lin(:,IT1) = 0.5 * mass(IT1,1) * l_vel_sqd(:,IT1);
    ke_ang(:,IT1) = 0.5 * mass(IT1,2) * a_vel_sqd(:,IT1);
end

% size of energy matrices
[re ce] = size(mgh);
if re < 100
    end

% Identify positive increments in energy; set negative increments to zero
% because do not want negative work
for IT1 = 1:ce
    for IT2 = 2:re
        % potential energy
        if mgh(IT2-1,IT1) < mgh(IT2,IT1)
mgh_pos(IT2-1,IT1) = mgh(IT2,IT1) - mgh(IT2-1,IT1);
else
mgh_pos(IT2-1,IT1) = 0;
end

% linear K.E.
if ke_lin(IT2-1,IT1) < ke_lin(IT2,IT1)
    ke_lin_pos(IT2-1,IT1) = ke_lin(IT2,IT1) - ke_lin(IT2-1,IT1);
else
    ke_lin_pos(IT2-1,IT1) = 0;
end

% angular K.E.
if ke_ang(IT2-1,IT1) < ke_ang(IT2,IT1)
    ke_ang_pos(IT2-1,IT1) = ke_ang(IT2,IT1) - ke_ang(IT2-1,IT1);
else
    ke_ang_pos(IT2-1,IT1) = 0;
end

% add columns and sum of columns
e1 = sum(sum(mgh_pos),2);
e2 = sum(sum(ke_lin_pos),2);
e3 = sum(sum(ke_ang_pos),2);
%% LINH SEPARATE HERE

% e1 = sum(sum(mgh_pos(tstart:tend,:)),2);
% e2 = sum(sum(ke_lin_pos(tstart:tend,:)),2);
% e3 = sum(sum(ke_ang_pos(tstart:tend,:)),2);
%
% for IT1 = 1:rv
%   mgh(:,IT1) = mass(IT1,1) * g * pos_y(:,IT1);
%   ke_lin(:,IT1) = 0.5 * mass(IT1,1) * l_vel_sqd(:,IT1);
%   ke_ang(:,IT1) = 0.5 * mass(IT1,2) * a_vel_sqd(:,IT1);
% end
% energy = e1 + e2 + e3;

energy = [e1, e2, e3];

MATLAB Program B2

%% start_rolling_MME_v2.m created 03/09/2015

% script to read in velocities and angular velocities from OpenSim Analysis
% tool xxx.sto files and calculate the positive increments (positive work)
% of rolling with the arms crossed and uncrossed
%
% CHANGE: _v2 now reads in Ixx, Iyy, and Izz from
% 'rolling_subj_mass_moi_v2.txt' file to account for all angular rotations.
% Change made to portion of file sent to function rolling_MME_calc_v2

clear all

% %%% Filtering
% % Nyquist freq
% Wn = 50/2;
% cutoff = 4; % cutoff frequency
% % Generate filter coefficients
% [B, A] = butter(6, cutoff/Wn)

%% Read in mass, moment of interia and rolling start and end times
% froot = '/Users/k945z449/Documents/MATLAB/Mahdi_Rolling/';
% froot = '/Users/k945z449/Dropbox/MATLAB_DropBox/Mahdi_Rolling/';
froot = '/Users/k945z449/Documents/WSU Research General/Rolling
Study/Mahdi_MMERolling_Data/';

% Read subject Mass and Moment of Inertia - first column is segment mass,
% second column is segment moment of inertia
% subj1 mass, subj1 MoI, subj2 mass, subj2 MoI, subj3 mass, ...
mass_moi = open_matrix([froot, 'rolling_subj_mass_moi_v2.txt']);

% Read subject (4 columns, 5 rows) rolling start (column1) and end (column2)
% times for arms crossed (columns 1-2) and uncrossed (columns 3-4) and
% trials (rows 1-5)

start_end = open_matrix([froot, 'rolling_subj_start_end_time.txt']);

% Note: there is no Subject_7, so skip this number

subjnum = [1 2 3 4 5 6 8 9 10 11];

trial = [1 2 3 4 5];

% Process Experimental data

count = 0;
for IT1 = subjnum
    for IT2 = 1:length(trial)
        count = count + 1;
        if IT1 == 4 & IT2 == 1
            p=1
        end
    end
end
mme_unx(count,:) = ['Subj_', int2str(IT1),'_trial_unx_',
int2str(IT2)],rolling_MME_calc_v2(froot, IT1, IT2, 0, mass_moi(:,4*IT1-3:4*IT1),
start_end(IT2,4*IT1-3:4*IT1));

mme_x(count,:) = ['Subj_', int2str(IT1),'_trial_x_',
int2str(IT2)],rolling_MME_calc_v2(froot, IT1, IT2, 1, mass_moi(:,4*IT1-3:4*IT1),
start_end(IT2,4*IT1-3:4*IT1));

end
end

% %%% original below

% % read in position data to position data matrix

% pos_data = open_matrix([froot, 'subject4_trial2_BodyKinematics_pos_global.sto']);

% % determine size of position data matrix

% [rp, cp] = size(pos_data);

% % filter data

% p_data = [pos_data(:,1), filtfilt(B, A, pos_data(:,2:cp))];

% % select y-coordinate position data

% pos_y = p_data(:,9:6:cp);

% % read in velocity data to velocity data matrix
C. WRAP CREATION IN OPENSIM MODEL

Right Chest Wrap
Left Chest Wrap

<table>
<thead>
<tr>
<th>:Chest_L - Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
</tr>
<tr>
<td>color</td>
</tr>
<tr>
<td>dimensions</td>
</tr>
<tr>
<td>display</td>
</tr>
<tr>
<td>display_preference</td>
</tr>
<tr>
<td>name</td>
</tr>
<tr>
<td>quadrant</td>
</tr>
<tr>
<td>translation</td>
</tr>
<tr>
<td>type</td>
</tr>
<tr>
<td>xyz_body_rotation</td>
</tr>
</tbody>
</table>
D. MATLAB PROGRAM FOR DATA NORMALIZATION

% start_EMGCMC_v1.m

clear all
clc

% Column 1 is time
EMGcol = [1, 26, 27, 28, 29, 32, 33, 34, 35];
OSimcol = [1, 192, 114, 154, 76, 242, 240, 294, 292];

froot1 = 'E:\Model Validation\Model Validation for EMG\'; %C:\CMC simulation\';
%froot1 = '/Users/k945z449/Downloads/CMCEMG/'; %C:\CMC simulation\';
froot2 = 'E:\Model Validation\Model Validation for EMG\';

% unxEMGfiles = dir([froot1,'**un_EMG.anc']);
%
% unxOSimfiles = dir([froot1,'**un_controls.sto']);
%
% xEMGfiles = dir([froot1,'**x_EMG.anc']);
%
% xOSimfiles = dir([froot1,'**x_controls.sto']);
%
%% Filtering
% sample frequency Hz
samplfreqEMG = 1500;
samplefreqOSim = 4000;

% cutoff freq Hz
cutoff = 6;

% Nyquist freq
WnEMG = samplfreqEMG/2;
WnOSim = samplefreqOSim/2;

% Generate filter coefficients
[B, A] = butter(6, cutoff/WnEMG);
[C, D] = butter(6, cutoff/WnOSim);

% Read subject (4 columns, 5 rows) rolling start (column1) and end (column2)
% times for arms crossed (columns 1-2) and uncrossed (columns 3-4) and
% trials (rows 1-5)
start_end = open_matrix(['froot2', 'rolling_subj_start_end_time.txt']);

%%% Note: there is no Subject_7, so skip this number
subjnum = [1 2 3 4 5 6 8 9 10 11];

% create counter
count = 1;
for IT1 = subjnum

% uncrossed rectify, filter, and with time column
unEMGdata = []; unEMGraw =[];
unEMGdata = open_matrix([froot1,'Subject', int2str(IT1), '_un_EMG.anc']);
unEMGraw = abs(unEMGdata(:,EMGcol(2:end)));
unEMG = filtfilt(B, A, unEMGraw);
unEMGwithtime = [ unEMGdata(:,EMGcol(1)),unEMG];

unOSimdata = []; unOSimraw =[];
unOSimdata = open_matrix([froot1,'Subject', int2str(IT1), '_un_states.sto']);
unOSimraw = abs(unOSimdata(:,OSimcol(2:end)));
unOSim = filtfilt(C, D, unOSimraw);
unOSimwithtime = [ unOSimdata(:,OSimcol(1)),unOSim];

xEMGdata = []; xEMGraw =[];
xEMGdata = open_matrix([froot1,'Subject', int2str(IT1), '_x_EMG.anc']);
xEMGraw = abs(xEMGdata(:,EMGcol(2:end)));
xEMG = filtfilt(B, A, xEMGraw);
xEMGwithtime = [ xEMGdata(:,EMGcol(1)),xEMG];
xOSimdata = []; xOSimraw = []; 

xOSimdata = open_matrix([froot1,'Subject', int2str(IT1), '_x_states.sto']);

xOSimraw = abs(xOSimdata(:,OSimcol(2:end))); 

xOSim = filtfilt(C, D, xOSimraw); 

xOSimwithtime = [ xOSimdata(:,OSimcol(1)),xOSim];

%start and end time file 

time = start_end(3,4*IT1-3:4*IT1);

%define start and end time 

 tstartunEMG = find(unEMGwithtime(:,1) == time(1,3));
 tstartunOSim = find(unOSimwithtime(:,1) == time(1,3));
 tendunEMG = find(unEMGwithtime(:,1) == time(1,4));
 tendunOSim = find(unOSimwithtime(:,1) == time(1,4));
 tstartxEMG = find(xEMGwithtime(:,1) == time(1,1));
 tstartxOSim = find(xOSimwithtime(:,1) == time(1,1));
 tendxEMG = find(xEMGwithtime(:,1) == time(1,2));
 tendxOSim = find(xOSimwithtime(:,1) == time(1,2));

%input start and end time and store files 

unEMG1 = unEMGwithtime(tstartunEMG:tendunEMG,:);
unOSim1 = unOSimwithtime(tstartunOSim:tendunOSim,:);
unOSimall (count).data = [unOSim1];
unOSimall (count).name = ['Subject', int2str(IT1), '_un_states.sto'];

xEMG1 = xEMGwithtime(tstartxEMG:tendxEMG,:);
xOSim1 = xOSimwithtime(tstartxOSim:tendxOSim,:);
xOSimall (count).data = [xOSim1];
xOSimall (count).name = ['Subject', int2str(IT1), '_x_states.sto'];

a(1,:) = max (unEMG1(:,2:end));
a(2,:) = max (xEMG1(:,2:end));
EMGmax1 = max (a);
EMGmax = [1 EMGmax1];

unEMGnorm = bsxfun(@rdivide,unEMG1, EMGmax);
unEMGall (count).data = [unEMGnorm];
unEMGall (count).name = ['Subject', int2str(IT1), '_un_EMG.anc'];

xEMGnorm = bsxfun(@rdivide,xEMG1, EMGmax);
xEMGall (count).data = [xEMGnorm];
xEMGall (count).name = ['Subject', int2str(IT1), '_x_EMG.anc'];

count = count + 1;

end

%interpolation%

count1 = 1;

for IT2 =1:10
    t= unEMGall(IT2).data(:,::);
    x= t(1,1):(t(end,1)-t(1,1))/100:t(end,1);
    y=interp1(t(:,1),t(:,2:end),x);
    unEMGallinter (count1).data = y;
    unEMGallinter (count1).name = ['Subject', int2str(IT1), '_un_EMG.anc'];

    t1= unOSimall(IT2).data(:,::);
    x1= t1(1,1):(t1(end,1)-t1(1,1))/100:t1(end,1);
    y1=interp1(t1(:,1),t1(:,2:end),x1);
    unOSimallinter (count1).data = y1;
    unOSimallinter (count1).name = ['Subject', int2str(IT1), '_un_states.sto'];

    t2= xEMGall(IT2).data(:,::);
    x2= t2(1,1):(t2(end,1)-t2(1,1))/100:t2(end,1);
    y2=interp1(t2(:,1),t2(:,2:end),x2);
    xEMGallinter (count1).data = y2;
xEMGallinter (count1).name = ['Subject', int2str(IT1), '_x_EMG.anc'];

t3 = xOSimall(IT2).data(:, :);

x3 = t3(1, 1):((t3(end, 1) - t3(1, 1)) / 100: t3(end, 1));
y3 = interp1(t3(:, 1), t3(:, 2:end), x3);
xOSimallinter (count1).data = y3;
xOSimallinter (count1).name = ['Subject', int2str(IT1), '_un_states.sto'];

count1 = count1 + 1;
end

for IT3 = 1:10

figure;
subplot (4, 4, 1);
plot (unOSimallinter(IT3).data(:, 1));
hold on
plot (xOSimallinter(IT3).data(:, 1), 'r');
title ('L Glute Max');
axis([0 100 0 1]);

subplot (4, 4, 2);
```matlab
plot (unOSimallinter(IT3).data(:,2));
hold on
plot (xOSimallinter(IT3).data(:,2), 'r');
title ('R Glute Max');
axis([0 100 0 1]);

subplot (4,4,5);
plot (unOSimallinter(IT3).data(:,3));
hold on
plot (xOSimallinter(IT3).data(:,3), 'r');
title ('L Glute Med');
axis([0 100 0 1]);

subplot (4,4,6);
plot (unOSimallinter(IT3).data(:,4));
hold on
plot (xOSimallinter(IT3).data(:,4), 'r');
title ('R Glute Med');
axis([0 100 0 1]);

subplot (4,4,9);
plot (unOSimallinter(IT3).data(:,5));
hold on
```
plot(xOSimallinter(IT3).data(:,5), 'r');
title('L. External Oblique');
axis([0 100 0 1]);

subplot(4,4,10);
plot(unOSimallinter(IT3).data(:,6));
hold on
plot(xOSimallinter(IT3).data(:,6), 'r');
title('R. External Oblique');
axis([0 100 0 1]);

subplot(4,4,13);
plot(unOSimallinter(IT3).data(:,7));
hold on
plot(xOSimallinter(IT3).data(:,7), 'r');
title('L. Pectoralis Major');
axis([0 100 0 1]);

subplot(4,4,14);
plot(unOSimallinter(IT3).data(:,8));
hold on
plot(xOSimallinter(IT3).data(:,8), 'r');
title('R. Pectoralis Major');
legend('unOSim','xOSim');
axis([0 100 0 1]);

% figure;

subplot (4,4,3);
plot (unEMGallinter(IT3).data(:,1));
hold on
plot (xEMGallinter(IT3).data(:,1), 'r');
title ('L Glute Max');
axis([0 100 0 1]);

subplot (4,4,4);
plot (unEMGallinter(IT3).data(:,2));
hold on
plot (xEMGallinter(IT3).data(:,2), 'r');
title ('R Glute Max');
axis([0 100 0 1]);

subplot (4,4,7);
plot (unEMGallinter(IT3).data(:,3));
hold on
plot (xEMGallinter(IT3).data(:,3), 'r');
title ('L Glute Med');
axis([0 100 0 1]);

subplot (4,4,8);
plot (unEMGallinter(IT3).data(:,4));
hold on
plot (xEMGallinter(IT3).data(:,4), 'r');
title ('R Glute Med');
axis([0 100 0 1]);

subplot (4,4,11);
plot (unEMGallinter(IT3).data(:,5));
hold on
plot (xEMGallinter(IT3).data(:,5), 'r');
title ('L External Oblique');
axis([0 100 0 1]);

subplot (4,4,12);
plot (unEMGallinter(IT3).data(:,6));
hold on
plot (xEMGallinter(IT3).data(:,6), 'r');
title ('R External Oblique');
axis([0 100 0 1]);

subplot (4,4,15);
plot (unEMGallinter(IT3).data(:,7));
hold on
plot (xEMGallinter(IT3).data(:,7), 'r');
title ('L Pectoralis Major');
axis([0 100 0 1]);

subplot (4,4,16);
plot (unEMGallinter(IT3).data(:,8));
hold on
plot (xEMGallinter(IT3).data(:,8), 'r');
title ('R Pectoralis Major');
legend ('unEMG','xEMG');
axis([0 100 0 1]);
end
E. AVERAGE SIMULATED MUSCLE ACTIVATIONS FROM COMPUTED MUSCLE CONTROL AND AVERAGE EXPERIMENTAL EMG

Average Simulated Muscle Activations from Computed Muscle Control (Solid Black Line; Dashed Line Represents ± 1 Standard Deviation) and Average Experimental EMG (Gray Area) Collected with Surface Electrodes from Ten Subjects Rolling with Arms Crossed
Average Simulated Muscle Activations from Computed Muscle Control (Solid Black Line; Dashed Line Represents ± 1 Standard Deviation) and Average Experimental EMG (Gray Area) Collected with Surface Electrodes from Ten Subjects Rolling with Arms Uncrossed
Left External Oblique

Right External Oblique

Left Petoralis Major

Right Petoralis Major