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Biomechanical evaluation of independent transfers and pressure relief tasks in persons with SCI: Pilot study

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Biomechanical Evaluation of Independent Transfers and Pressure Relief Tasks in Persons with SCI: Pilot Study

by

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of the requirements for the degree of
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Biomechanical Evaluation of Independent Transfers and Pressure Relief Tasks in Persons with SCI: Pilot Study

Tony J. Cresta

ABSTRACT

Persons with paraplegia who use a manual wheelchair for mobility are at high risk for overuse injuries in the upper extremities. Years of shoulder overuse performing transfers, wheelchair propulsion, dressing, bathing, and household chores, (activities of daily living or ADL) leads to an increased incidence of cumulative trauma to the shoulders.

Few studies have addressed the stressful task of wheelchair transfers among SCI individuals. The goal of this pilot study is to develop valid and reliable measurement technologies to quantify shoulder musculoskeletal stressors during wheelchair transfers and pressure relief tasks among individuals with SCI.

Using a standard wheelchair, 10 participants were asked to perform 3 typical pairs of independent transfer tasks: wheelchair to/from bed, wheelchair to/from commode, and wheelchair to/from vehicle. Also, two pressure relief tasks (P/R) were performed sitting in a wheelchair, one using the armrest and one using the wheels.

By observation, the transfers in descending order from the most demanding to the least demanding were as follows: vehicle, commode, and bed. During a P/R using the wheels there is a 40% greater max shoulder force and a 47% greater mean shoulder force than when using the armrest. The max shoulder force of over 1000 N is generated at the initial push off, during a P/R using the wheels, then the force drops 45% to an average of 558 N. The max shoulder force of 722 N at the initial push off, during a P/R using the Armrest, drops 48% and then averages 378 N.

During a P/R using the wheels there is a 104% greater max shoulder torque and a 17% greater mean shoulder torque than when using the armrest. As in the initial large amount of shoulder force there is also a large amount of shoulder torque that drops 77% during a P/R using the wheels. The shoulder torque decreases 62% during a P/R using the armrest. Because of the greater distance the body’s Center of Mass (COM) travels during the P/R using the armrest, 24% more work is done.

Chapter 1

Introduction

1.1 Overview

In the past individuals with spinal cord injury (SCI) did not enjoy long productive lives. Since most patients that incur an SCI are young and are living longer lives, concerns exist about maintaining independence with activities of daily living (ADL) over a longer period of time. With advances in medicine and US legislation (The Americans with Disabilities Act 1990) that address the needs of the physically challenged, funding was made available to allow these individuals to work and enjoy activities just the same as the general population. Longer life spans and increased activities, caused individuals with SCI to be concerned with maintaining their ability to perform transfers, wheelchair propulsion, dressing, bathing, and household chores -- their activities of daily living (ADL).

Deterioration of the upper extremity (UE) has a detrimental effect on the independence, quality of life, and even the life expectancy of individuals following SCI. Few studies have addressed transfers among SCI individuals. Increased incidence of cumulative UE trauma following years of biomechanical loading dramatically affects the quality of life of persons with SCI, adding to their disability and diminishing their independence.

1.2 Statement of the Problem

It is estimated that the annual incidence of SCI is approximately 11,000 cases each year. [1, 2] The number of people in the United States who were alive in July 2004 who have SCI has been estimated to be 247,000 persons, with a range of 222,000 to 285,000 persons. 47% of the people in this group have lesions below T-1 (paraplegia).

The National Health Interview Survey on Disability reported in 1999 that more than 2.3 million individuals in this country have disabilities requiring the use of a wheelchair [1]. Manual wheelchair users (MWCUs) are included within the disability groups of spinal cord injury (SCI) -- lower-limb amputation, stroke, multiple sclerosis, rheumatoid arthritis, spina bifida, poliomyelitis, and hip fracture, as well as other groups. More than 176,000 veterans use manual wheelchairs for mobility, with 44,000 manual wheelchairs distributed annually at a cost of over $28 million, according to the Veterans Health Administration

Individuals with paraplegia must perform ADL without the use of their lower extremities. As such, these tasks are primarily performed with the use of the upper extremities (UE), mainly the shoulder girdles. Following the SCI, the UE must be able to withstand the cumulative forces of weight bearing during mobility and transfers.

Many wheelchair users experience upper extremity pain that interferes with essential activities of daily living such as wheelchair propulsion, driving, dressing, and transfers. Upper extremity weight-bearing activities and chronic overuse have both been implicated in the development of soft tissue disorders and degenerative changes in the shoulder joints.

1.3 Missing Elements in the Research Knowledge

Previous studies of SCI subjects' wheelchair mobility and transfers have relied on electromyographic [3-7], kinematic[8, 9], or ground reaction force data[10]. Comparatively few studies have addressed transfers other then pressure relief tasks, a simple posterior transfer, and a transfer to a 10 cm. elevated, or lower surface [7, 10]. A review of the literature revealed no investigation which integrated each of these data collection modes, or analyzed the joint moments of SCI subjects during transfers. This data is needed to accurately evaluate the UE joint stresses, muscular contributions, and the inter-relationship between trunk position and UE functional demands of SCI patients. Recent innovations in motion analysis, mathematical modeling and computer simulation methods provide researchers with additional analytical tools to help strengthen intervention planning for UE preservation in SCI patients. Through advanced technology, comprehensive clinical evaluation, and experimental research, clinical interventions to help ameliorate shoulder pain and injuries can be developed.

1.4 Anatomy

The shoulder consist of 2 main bones -- the scapula and humerus -- which form a ball and socket joint. The motion of the scapula and humerus are simultaneously continuous at both flexion and abduction of the shoulder joint. During the first 30 to 60 degrees of elevation, the scapula seeks, in relationship to the humerus, a position of stability. Therefore the early phase of motion is irregular, and is characteristic for each individual. It seems to depend upon the location the scapula occupies in the subject when at rest. This phase is termed the "setting phase" since it is related to the setting action of the muscles. After this phase the relationship of humeral and scapular motion are constant with the ratio being 2:1 in degrees, respectively. The total range of scapular motion is not more than 60° and the humerus, not more than 120°.

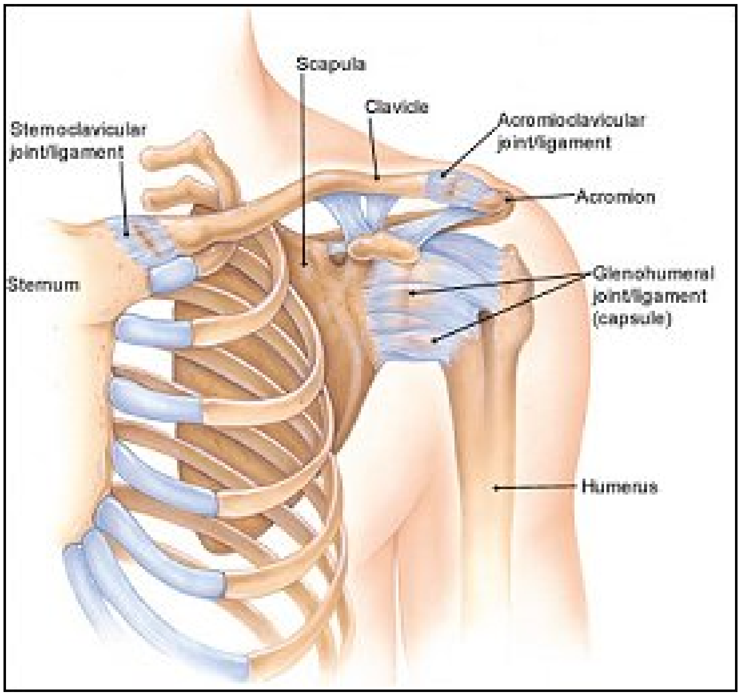


Figure 1. Shoulder Anatomy

The deltoid muscle consists of three heads: anterior, medial, and posterior. On both sides, the deltoid muscles are important in attaching the shoulder girdle to the arm. They originate from the: inferior surface of the lateral third of the clavicle, acromion, and spine of the scapula. They insert into the deltoid tuberosity. Acting as a unit, the deltoid acts to abduct the arm at the glenohumeral joint. However, the anterior fibers assist in flexing and medially rotating the arm, whereas the posterior fibers extend and laterally rotate.

On the anterior of the chest is the pectoralis major muscle. The pectoralis major flexes, adducts, and rotates the humerus medially.

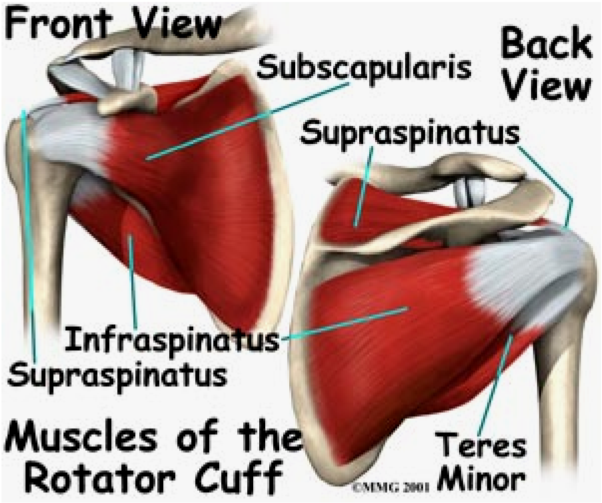


Figure 2. Muscles of the Rotator Cuff

The rotator cuff muscles are called the supraspinatus, infraspinatus, teres minor, and subscapularis. The rotator cuff connects the humerus with the scapula (shoulder blade) and helps raise and rotate the arm. As the arm is raised, the rotator cuff also keeps the humerus tightly in the socket (glenoid) of the scapula. The supraspinatus assists the middle deltoid in abducting the humerus. The infraspinatus, subscapularis and teres minor assist the latissimus dorsi muscle by pulling the humerus down and to the rear.

The scapula rotators -- upper trapezius, levator scapulae, and upper serratus anterior, constitute a unit which performs three functions, passive support of the shoulder, active elevations of the shoulder, and the upper component of the force necessary for scapular rotation. With elevation of the arm, both in flexion and abduction, there is a linear rise in force reaching its maximum when the arm is above the head slightly above 90 degrees.

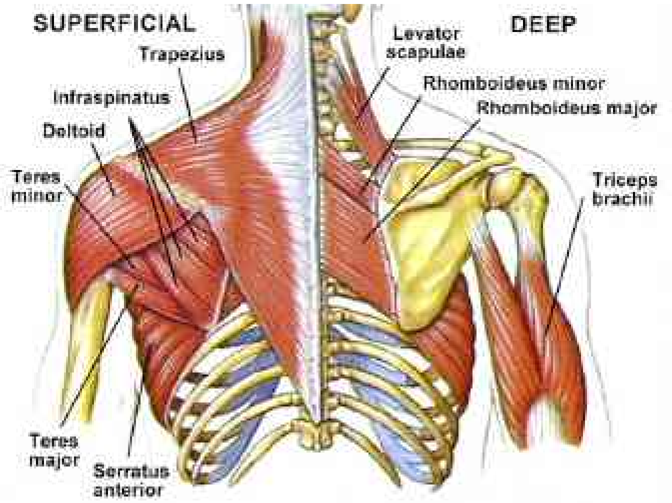


Figure 3. Posterior Musculature of the Upper Torso

The inferior part of the trapezius, subclavius, and pectoralis minor contribute to the downward motion of the scapula. The rhomboid muscles, much like the middle trapezius are most active during scapular adduction, but also contribute to inward rotation and elevation.

Chapter 2

Current Status of the Work

2.1 Pain Demographic Studies

Paraplegic patients rely on their upper extremities for transport activities such as wheelchair propulsion and transfers. Unlike the joints of the lower extremities (LEs), with structures specialized for strength under load, the joints of the UEs are characterized by structures specialized for range of motion, which predispose them to injury when used to replace LE functions. This is known as overuse syndrome. Several studies have documented pain as a consequence of overuse syndrome of the UEs associated with paraplegia. However, whether this is due to wheelchair propulsion or transfer activities is undetermined.

Gellman et al studied 84 paraplegic patients whose injury level was T2 or below and who were at least 1 year from spinal cord injury (SCI). [11] 57 (67.8%) of the patients had complaints of pain in one or more areas of their UEs. The most common complaints were shoulder pain and/or wrist pain, with 25 (30%) complaining of shoulder pain during transfer activities. Symptoms were found to increase with time from SCI.

Curtis et al compared the prevalence and intensity of shoulder pain experienced during daily functional activities in individuals with tetraplegia and individuals with paraplegia. [1] There were 195 subjects, of whom 52 were women, who met inclusion criteria of 3 hours per week of manual wheelchair use and at least 1 year since onset of spinal cord injury. More than two-thirds of the sample

reported shoulder pain since beginning wheelchair use, of which 59% of the subjects had tetraplegia and 42% of the subjects had paraplegia.
Dalyan et al. administered a questionnaire to 170 persons with SCI designed to describe the frequency and severity of UE pain in persons with SCI, the association with specific activities, and the therapy received. [12] Of the 130 persons (38 paraplegic, 38 tetraplegic patients) who responded, 76 (58.5%) reported UE pain -- 71% had shoulder pain, 53% had wrist pain, 43% had hand pain, and 35% had elbow pain. Pain interfered with transfers in 65% (36/55) of the patients who were performing them. The functional activities associated with pain were pressure relief movements, transfers, and wheelchair mobility. 63% sought medical treatment for pain and, of those, 90% received physical therapy, drug treatment or massage. Although only 27% had wheelchair or home modification or joint protection education, these approaches were helpful for almost all, and were extremely helpful for 63.6% of the patients. [12]

Subbarao et al surveyed 451 SCI patients by questionnaire. In addition, 30 patients were available for clinical observation and evaluation. [13] Results indicated that wrist and shoulder pain were more prevalent than previously indicated. 72.7 percent of respondents reported some degree of chronic pain in one or both of these areas. Wheelchair propulsion and transfers caused most of the pain and also increased the degree of pain. They concluded that alternative methods for wheelchair propulsion and transfers, which would lessen stress and cumulative trauma, need to be developed for SCI patients in order to diminish the incidence of chronic upper limb pain.

Finley et al looked at 52 manual wheelchair users -- 26 athletes and 26 non-athletes -- and no difference was found in the incidence of shoulder pain, past or present, between athletes and non-athletes. [14] 61.5% (32/52) of the subjects reported experiencing shoulder pain. Years since onset of disability and duration of wheelchair use were found to be greater in individuals who reported a history of shoulder pain. Of the painful shoulders tested, 44% revealed clinical signs

and symptoms of rotator cuff impingement, while 50% revealed signs of biceps tendonitis. Instability was found in 28% of the painful shoulders.
Bayley et al examined 94 persons with paraplegia for pain during transfer activities.[15] Thirty-one patients reported pain on transferring, and twenty-three of these patients were found to have a chronic impingement syndrome with subacromial bursitis. Arthrography of the shoulder was done for each of these twenty-three patients, fifteen of which were found to have a tear of the rotator cuff. Five of the thirty-one patients were found to have aseptic necrosis of the head of the humerus. They measured the intra-articular pressure in the shoulder during transfers, and found that this pressure exceeded the arterial pressure by a factor of 2.5.

Gironda et al. surveyed 1675 veterans with paraplegia (PP).[16] Of the 46% who answered, approximately 81% of the respondents reported at least a minimal level of ongoing unspecified pain and 69% experienced current UE pain. Shoulder pain intensity was most severe during the performance of wheelchair-related mobility and transport activities, suggesting that UE pain may have a significant impact on functional independence. Duration of wheelchair use modestly predicted shoulder pain prevalence and intensity, but age and the interaction between age and duration of wheelchair use did not.

2.2 Radiological Studies

As reported by Barber, D. B. & Gall, N.G. in their article in Paraplegia, the shoulder of the wheelchair dependent paraplegic is subject to overuse injury with subsequent pain. [17] The major overuse syndromes observed include soft tissue injuries and secondary degenerative arthritis. This report presents a case in which bilateral osteonecrosis of the humeral heads was found to be the source of pain in the shoulders of an active paraplegic without any evidence of disease or medical treatment associated with the development of osteonecrosis.

Osteonecrosis should be entertained in the differential diagnosis of overuse injuries of the shoulder in paraplegia.

2.3 Body Composition and its Effect on SCI Persons

The prevalence of diseases associated with obesity, such as cardiovascular disease and diabetes mellitus, is higher in the spinal cord injury (SCI) population. The mortality rate for cardiovascular disease is 228% higher in the SCI population which is related to physical activity level, the level of the spinal cord lesion, and time post injury. [18] Physically active SCI men and women have above-average fat mass (16 to 24% and 24 to 32%, respectively, compared with 15% for able-bodied men and 23% for able-bodied women), while sedentary SCI individuals have 'at-risk' levels of body fat (above 25% and 32%, respectively).

2.4 Muscle Kinetics and Kinematics

Bayley et al reported that paraplegic patients with a lower lesion level may be able to partially support their bodyweight during transfers using functional abdominal or spinal muscles. [15] They considered this capacity vital to relieving the shoulder girdle of excessive transfer forces. Pressure measurements were taken in the subacromial area of the shoulder joint. The position of the catheter was verified, arthrographically. Continuous pressure measurements were recorded, while the patient performed 6 different tasks, one being an active transfer from a wheelchair to a bed. Unweighted active, gentle flexion and extension activity produced peaks of pressure in the range of 543 kg/m^2 – 1087 kg/m^2. During the transfer the peak pressures rose to as much as 3606 kg/m^2. During a transfer from a wheelchair to any object, the weight of the body is transferred from the trunk through the clavicle and scapula across the glenohumeral joint to the humerus. The pressure in the shoulder joint during transfers exceeds the mean arterial pressure by more than 2 ½ times. The belief is that this high pressure in conjunction with abnormal stress across the subacromial area during a transfer or propulsion of a wheelchair, contributes to the high rate of shoulder problems in paraplegic patients. Most of the problems involve the muscles and ligaments around the shoulder joint, especially the rotator cuff. Perry et al in evaluating 12 asymptomatic, low level paraplegic patients for the activation of 12 shoulder muscles (on the right side) during the performance of depression transfers, reported 3 transfer phases -- preparatory, lift and descent. [5] Muscle activity was categorized by intensity – high (> 50%), Moderate (25-50%), and low (< 25%). The lift phase required the greatest muscular effort by the lead arm, with peak activity of the pectoralis major (81% manual muscle test (MMT)) and moderate action of the serratus anterior (47% MMT), latissimus dorsi (40% MMT), and infraspinatus (37% MMT). In the trailing arm there was strong serratus anterior activity (54% MMT), while the pectoralis major (49% MMT), infraspinatus (45% MMT), anterior deltoid (44% MMT), and supraspinatus (38% MMT) exerted moderate effort. The descent phase displayed the least intense muscle activation, consistent with the greater efficiency of eccentric muscular activation. Of particular note was the minimal activity in the middle and posterior heads of the deltoid as well as the middle trapezius during all phases of the transfer and the low activity of the long head of the triceps in both arms throughout the tasks. Perry proposed that trunk elevation was accomplished mainly by sternal pectoralis major and latissimus dorsi activity. Lateral body displacement required other muscles to control the elevated body. Rotator cuff muscles, together with the anterior deltoid, provided anterior glenohumeral wall protection. Lower serratus anterior stabilized the scapulothoracic joint and contributed to lateral movement. Assessment of depression transfer skill should not be based on the ability to lift body weight. Movement of the trunk required strong activity of key shoulder muscles. Differences in leading and trailing arm EMG intensities will assist in modifying transfer methodologies in individuals with weakness, strength imbalances, and shoulder pathologies.

Reyes et al set out to define the demand on the shoulder musculature during performance of a weight relief raise. Intramuscular electromyographic activity of 12 shoulder muscles was recorded in 13 pain-free subjects with paraplegia while elevating the trunk from a sitting position. [4] The weight relief took an average of 2.6 sec for a subject to complete the 3 phases of the raise maneuver (load, lift, and hold). Trunk elevation and bilateral elbow extension (85 - 17 degrees flexion) were the primary movements while the latissimus dorsi (58% MMT), the long head of triceps brachii (54% MMT), and the sternal portion of pectoralis major (32% MMT) were the most active muscles. Strong latissimus dorsi activity was noted during the hold phase (51% MMT), while the triceps and sternal pectoralis major demonstrated only moderate activation. (Again another study that has lower tricep activity than one would expect.) With the exception of the subscapularis (16% MMT during loading) and the lower serratus anterior (12% MMT during the lift), none of the rotator cuff, deltoid, or scapular muscles exceeded 10% MMT. Thoracohumeral muscle activity, by transferring the load on the humerus directly to the trunk, functionally circumvented the glenohumeral joint. This would reduce the potential for impingement of the rotator cuff.

Seelen et al reported that the increased latissimus dorsi and trapezius muscle activation observed in sitting SCI subjects served to stabilize their sitting posture.[19]

Gagnon et al studied three-dimensional kinematic analysis and surface EMG of 10 male adults with complete spinal cord injury (C7 to L2) to examine movement patterns and muscular demands in individuals with SCI during posterior transfers. [7] The first transfer was a backward movement on an even surface with hands placed symmetrically alongside the body (even task). For the second transfer the subjects had to raise themselves in a backward movement to an elevated surface of 10 cm in height. For this elevated task subjects had to use three hand placement strategies: both hands on the lower surface, both hands on the elevated surface, and one hand on each of these surfaces. Kinematic variables that described the positions and angular displacements of the head, trunk, shoulder and elbow were obtained by videotaping markers placed on the subject segments. To quantify the muscular demand, subjects were seated on the chair of the Biodex dynamometer and performed activities to stimulate the six muscles of the shoulder girdle to establish EMG max. The joint positions selected for these tasks corresponded to the joint positions used by the subject during the experimental tasks. EMG data were recorded for the biceps, triceps, anterior deltoid, pectoralis major, latissimus dorsi and trapezius muscles of the dominant upper extremity during posterior transfers using surface electrodes. The mean muscular demands were calculated for every muscle during the lift phase of the transfers. The lift phase was determined by pressure-sensitive contacts. All subjects were able to execute the posterior transfers on an even surface, whereas nine subjects completed at least one of the transfers to the elevated surface. A forward-flexion pattern at the head and trunk was observed when either one or two hands remained on the lower surface, whereas a lift strategy was seen when both hands were placed on the elevated surface. Transferring to the elevated surface with hands on the lower surface required an inferior electromyographic muscular utilization ratio (EMUR) than the transfer on the even surface for all muscles. The EMUR was obtained by dividing the EMG recorded during the transfer by the EMG max obtained on the dynamometer. The result was multiplied by 100 to give a percentage. The lowest EMURs were calculated for the transfer to the elevated surface with hands on the lower surface (triceps (18%), pectoralis major (53.8%), trapezius (66%) and latissimus dorsi (24.5%) while performing the same transfer with hands on the elevated surface generated the highest EMURs (triceps (40.2%), anterior deltoid (73.2%), trapezius (83.6%) and latissimus dorsi (55.3%). Subjects presented different movement characteristics and muscular demands during the posterior transfers. It is suggested that the forward-flexion pattern improves the dynamic trunk stability and reduces the muscular demand required to transfer. The high muscular demand developed when hands were positioned on the elevated surface might be due to increased postural control demands on the upper limb and reduced angular momentum.

Finley et al wanted to compare scapular kinematics and muscle function during the performance of transfers in groups of MWCUs with and without shoulder impingement. [8] It was hypothesized that (1) MWCUs with shoulder impingement would demonstrate different scapular kinematics and muscle activity compared to MWCUs without the pathology and (2) muscle activation patterns would be different between the two transfer tasks. MWCUs with impingement performed transfers with less thoracic flexion, increased scapular internal and reduced humeral internal rotation as compared with those without the pathology. The scapular function during a leading limb and trailing limb transfer is different. The trailing limb had increased serratus anterior and lower trapezius activity with downward scapular rotation and reduced scapular posterior tipping compared with the lead limb transfer. In an effort to further understand the mechanism of shoulder impingement in this population, factors such as the task repetition, magnitude of joint loading and specific impairment and disability factors need to be investigated.

Wang et al, in assessing wheelchair to seat transfers of varying heights among six asymptomatic non-impaired subjects, reported that transfers to lower height seats generated greater ground reaction forces and greater triceps brachii and posterior deltoid activation to "overcome the force of the body gravity".[10] This study explored how the reaction force and muscle activity change when transferring from a wheelchair to three different heights. Six able-bodied male subjects, ages ranging from 20 to 25 years old, who had their legs tied together to help control movement, performed the three transfer tasks (they still had the use of trunk stabilizing muscles, so it was not truly representative of SCI Population). The three seat heights used were 40 cm (toilet height), 50 cm (wheelchair height), and 60 cm (bed height). Transfers to a higher seat resulted in a shift of the "friction force" from primarily anterior-posterior to more medial-lateral and required a greater muscular contribution from the biceps brachii muscle. Wang et al reported that equal wheelchair and destination heights required less muscular effort during transfers.

Musculoskeletal injuries can result from overuse or incorrect use of manual wheelchairs, and can hinder rehabilitation efforts. Rodgers et al investigated wheelchair propulsion biomechanics of spinal-cord-injured, non-athletic wheelchair users. They noted that with fatiguing wheelchair propulsion, the subject’s physical characteristics and the state of fatigue influences the risk of injury. Twenty male paraplegic patients were videotaped during propulsion to fatigue on a stationary, instrumented wheelchair positioned on a roller with adjustable frictional resistance. Peak handrim force was significantly correlated with concentric shoulder flexion and elbow extension isokinetic torques. Significant changes ($p < 0.05$) with fatigue were found in increased peak handrim force, decreased ulnar/radial deviation range of motion, and increased trunk forward lean. Of the three upper extremity joints, the highest calculated joint moments were found in shoulder flexion ($p < 0.05$). These biomechanical results suggest that potentially harmful changes occur with fatigue, and that the shoulder may be the most prone to musculotendinous-type overuse injury.[20]

Hobson et al reported that decreased trunk stability combined with the posture imposed by wheelchair seat configuration necessitated that SCI subjects assume a biomechanically abnormal sitting position characterized by a "C" shaped spinal kyphosis, an extended cervical spine, a flattened lumbar spine, and a posteriorly tilted pelvis. They reported that, in general, SCI subjects sit in a neutral posture with approximately 15 degree more posterior pelvic tilt than non-spinal cord injured subjects. It has been postulated that loss of voluntary trunk stability, combined with the posture imposed by the configuration of the wheelchair seat, biomechanically necessitates that a person with diminished trunk control assume an abnormal sitting posture.[21]

2.5 Summary

Recent innovations in mathematical modeling and motion analysis, provides researchers with additional analytical tools to help strengthen intervention planning for UE preservation in SCI patients. Through advanced technology, comprehensive clinical evaluation, and experimental research, clinical interventions to help lessen shoulder pain and injuries can be developed.

Deterioration of the UE has the potential to be extremely detrimental to the independence, quality of life, and even the life expectancy of SCI subjects. Transfer studies among SCI subjects should consider factors including age, overall medical status, length of time since disability, wheelchair transfer strategies, muscular strength, physical strain of ADL, body mass and composition, and UE injury history. Biodynamic SCI subject transfer strategy studies should combine three dimensional kinematic, kinetic and electromyographic data. The combination of these data sets will enable a more accurate depiction of the demands placed on the UE, particularly at the shoulder joint.

Chapter 3

Methods and Procedures

3.1 Research Design

This was a descriptive study to quantify the biomechanical stresses on persons with paraplegia while performing independent transfers and pressure relief tasks. A convenience sample of 10 subjects who met the inclusion criteria was selected. Transfers were performed between a wheelchair and; bed, commode, and vehicle mock-up. Data was captured using the Vicon 460 Motion Analysis System, EMG, force gloves, and questionnaires.

3.2 Sample

A convenience sample of 10 persons with paraplegia (T3-L3) was recruited from the James A Haley Veteran's Hospital Tampa. No adverse events were experienced by any of the participants, nor did any elect to remove themselves from the study.

3.2.1 Inclusion Criteria

The inclusion criteria for the subjects included the following:

1. Veterans with paraplegia who use manual wheelchairs for mobility.
2. Age range limited to 18 to 65 years, representative of an adult population.
3. Candidates should be at least 6 months post-SCI to have developed experience in transfers.

4. Level of spinal cord injury was limited to ASIA a classification at T2 through L5 level to standardize physical capabilities.
5. Candidates must be able to perform independent transfers, with or without use of assistive devices.

3.2.2 Exclusion Criteria

The exclusion criteria for the subjects included the following:

1. Candidates who presented clinical evidence of severe musculoskeletal disorders of the upper extremity or other physiological impairment which would limit their performance of the required transfer tasks were precluded from participating in this pilot study.
2. Candidates with significant cognitive impairment were excluded as evaluated in clinical screening.

3.3 Subject Recruitment, Screening, and Selection Criteria

3.3.1 Recruitment

Potential candidates were selected from the list of 1,100 veterans in the SCI Registry at the Tampa VAMC and were invited to participate. Additionally posters were displayed in the foyer of the SCI building of the James A Haley Veteran’s Hospital inviting SCI outpatients to contact us for more information.

3.3.2 Screening

The candidates were pre-screened over the telephone. Potential candidates were screened in the lab to assure the veterans met inclusion/exclusion criteria.

Manual muscle testing was performed with the aid of a handheld dynamometer to quantify muscular force output (Nicholas Manual Muscle Tester, Lenox Hill, NY). Shoulder strength was measured in: abduction, flexion and extension, internal and external rotation (Appendix A). Range of motion (ROM) was measured by an occupational therapist using a hand held goniometer (Appendix B).

Subjects were asked to complete a pain questionnaire (end range descriptors of no pain, extreme pain), which was modified to consider only shoulder, arm, and hand-related pain (Appendix C). The 4-item Physical Interference Subscale of the Fear Avoidance Beliefs Questionnaire (FABQ) was used. Recent empirical findings suggest that the FABQ is a psychometrically superior measure of the same construct assessed by the TSK.

3.3.3 Selection

A board certified physician who practices in Spinal Cord Injury Medicine performed a physical evaluation of each candidate to verify upper extremity and spine integrity and thereby determine their eligibility in the study, which included of a review of the candidates historical file, functional strength testing and ROM (Appendix D). The first 10 candidates who met the inclusion criteria participated in the study.

3.4 Study Population Characteristics

3.4.1 Subject Demographics

Following informed consent, all subjects completed a general demographic questionnaire (Appendix E). This one-page questionnaire includes standard questions pertaining to age, gender, race, occupational history and participation in recreational activities. A health questionnaire was completed by each participant (Appendix F), which specifically addressed historical considerations, including, level of injury, duration of injury, medication usage and secondary conditions.

3.4.2 Subject Anthropometry

A series of anthropometric measures were taken and recorded. Standard anthropometry measures of body segment link lengths, such as arm length, seated height, leg length, etc. were recorded using an anthropometer (Appendix G). Height and weight were measured, from which Body Mass Index (BMI) was computed.

3.5 Measurement

Objective data was captured using the Vicon 460 Motion Analysis System, EMG, force gloves, and questionnaires. Each of these is described in detail below.

3.5.1 Vicon Motion Analysis

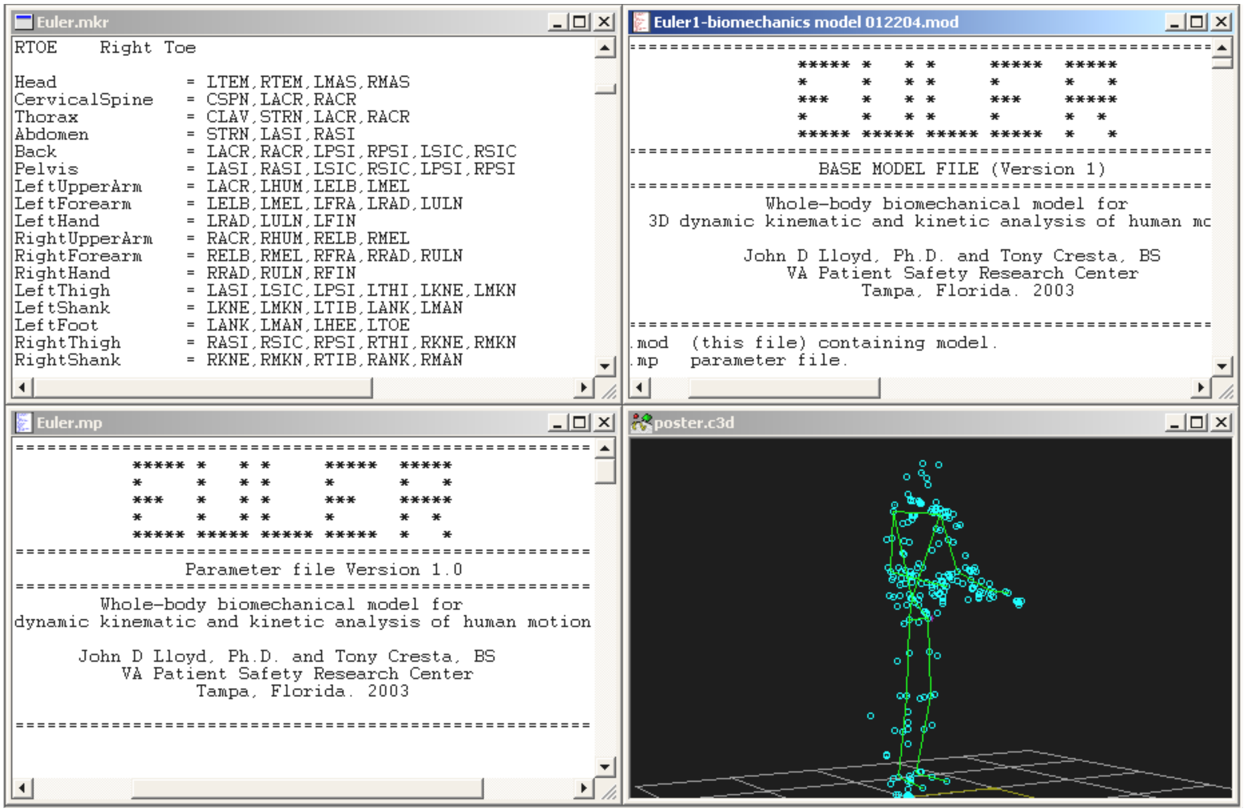
Motion of the subjects was captured by the Vicon 460 Motion Analysis System (www.vicon.com). This system uses an array of near-infrared stroboscopes and cameras to capture reflections from reflective spheres that are adhered to the body. Position data from these sensors was used to drive a 3-dimensional computer representation. Force data was collected simultaneously using force sensing resistors incorporated into the palm area of gloves worn by the participants.

3.5.1.1 Hardware

The Vicon 460 Motion Analysis System is a technology that is used to capture dynamic human motion. Optical-reflective markers were placed on the skin of the participants. The marker was tracked by a matrix of six wall-mounted near infra-red cameras and computed on a frame-by-frame basis at 120Hz. Since this is an optical technology, the integrity of this system may have been compromised due to occlusions. Typically, the workspace is cleared to ensure minimal visual interference between the markers and cameras. However, the proposed study required the utilization of bulky hospital equipment, such as a hospital bed, a simulated vehicle/van seat cabin, and a commode, which occasionally caused occlusions. A new marker set was devised for the Vicon 460 Motion Analysis System used in this study -- triad marker sets that were placed on rigid body segments, such as the upper and lower extremities. These triads raised the reflective markers above the surface of the skin by approximately fifteen millimeters. This had dramatic implications for improving line-of-site to multiple cameras within the array. These triads also afforded marker redundancy and thereby the opportunity to replace temporarily occluded adjacent markers by using a programmable replacement function in the Vicon BodyBuilder program code.

3.5.1.2 Software

Computational biomechanics programs are afforded by the manufacturer, Vicon, for Gait and Balance clinicians as well as the motion picture industry, as these are the principal markets for this technology. Dr. John Lloyd has developed new computational biomechanics programs using the Vicon BodyBuilder software to specifically calculate internal biomechanics of the human musculoskeletal system that are more appropriate for patient handling operations.



```
RTOE     Right Toe

Head            = LTEM,RTEM,LMAS,RMAS
CervicalSpine   = CSPN,LACR,RACR
Thorax          = CLAV,STRN,LACR,RACR
Abdomen         = STRN,LASI,RASI
Back            = LACR,RACR,LPSI,RPSI,LSIC,RSIC
Pelvis          = LASI,RASI,LSIC,RSIC,LPSI,RPSI
LeftUpperArm    = LACR,LHUM,LELB,LMEL
LeftForearm     = LELB,LMEL,LFRA,LRAD,LULN
LeftHand        = LRAD,LULN,LFIN
RightUpperArm   = RACR,RHUM,RELB,RMEL
RightForearm    = RELB,RMEL,RFRA,RRAD,RULN
RightHand       = RRAD,RULN,RFIN
LeftThigh       = LASI,LSIC,LPSI,LTHI,LKNE,LMKN
LeftShank       = LKNE,LMKN,LTIB,LANK,LMAN
LeftFoot        = LANK,LMAN,LHEE,LTOE
RightThigh      = RASI,RSIC,RPSI,RTHI,RKNE,RMKN
RightShank      = RKNE,RMKN,RTIB,RANK,RMAN
```

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                ***** *   * *     *****  *****
                *     *   * *     *      *   *
                ***   *   * *     ***    *****
                *     *   * *     *      *  *
                ***** ***** ***** *****  *   *
=======================================================
                 BASE MODEL FILE (Version 1)
=======================================================
              Whole-body biomechanical model for
  3D dynamic kinematic and kinetic analysis of human mc

             John D Lloyd, Ph.D. and Tony Cresta, BS
                 VA Patient Safety Research Center
                      Tampa, Florida. 2003

=======================================================
.mod  (this file) containing model.
.mp   parameter file.
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======================================================
                Parameter file Version 1.0
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        Whole-body biomechanical model for
dynamic kinematic and kinetic analysis of human motion

      John D Lloyd, Ph.D. and Tony Cresta, BS
          VA Patient Safety Research Center
                 Tampa, Florida. 2003

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Figure 4. Vicon BodyBuilder Software

The new program code defined how sets of markers were linked to represent rigid body segments, including head, torso, pelvis, etc. (Appendix I). Calculations were then performed within the model to accurately compute internal joint centers. Static anthropometry of the human participant can be calculated by the model. Distances between adjacent joint centers were used to compute segment lengths. Segment weights were determined as a function of total body mass. Segment center of mass locations were then computed as a proportion of segment length. Joint Angles between adjacent rigid body segments were computed within the model on a frame-by-frame basis. Velocity and acceleration derivatives of linear and angular motions were also computed with hi-fidelity. Loads applied at the hands were measured dynamically using a pair of force sensing resistors. Data was captured at 120Hz and streamed into the Vicon software for further analysis. Joint forces were thus computed dynamically within the model as a function of externally applied loads and the sum of distal segment weights.

3.5.2 Gloves with Force Sensing Resistors

Instrumented gloves were developed using force-sensing resistor (FSR) technology built into the palmar surface of fingerless gloves. These were used to dynamically capture external loading at the hands. Output from the FSRs was carefully calibrated using a Chatillon force gauge and was interfaced to the Vicon system through an A/D board.

Figure 5. Instrumented Gloves

3.5.3 EMG System

An eight-channel electromyography data acquisition technology was incorporated into the Vicon 460 Motion Analysis System so that researchers could simultaneously capture muscle activity data for up to eight major muscle groups, 4 on the left side and 4 on the right side of the body, and integrate this data with biomechanical information from the Vicon BodyBuilder program.

3.6 Description of Biomechanics Research Laboratory

All data collection for this study was performed in the biomechanics research lab at the VISN8 Patient Safety Center, in Tampa FL. This research lab, which occupies 1000 sq. ft., was originated in 1998 with funding from VHA Rehabilitation R&D service and includes the following state-of-the-art measurement systems: VICON 460 and HumanTRAC 3D human motion tracking, Fasstech digital electromyography, X-sensor pressure mapping, video thermography, laser Doppler measurement, Polar heart rate monitor, force measurement system, and LabView virtual instrumentation. This lab is staffed with a PhD ergonomist, a PhD biomechanist, a MS biomechanist and graduate students. The lab serves as a magnet to attract graduate students and faculty from the USF, College of Engineering, Department of Biomedical Engineering. These laboratory capabilities are used to scientifically examine patient, provider, and technology defenses to prevent falls, bedrail entrapments, wandering, and pressure ulcers, while promoting safe patient handling and movement.

Figure 6. Biomechanics Research Laboratory

3.7 Data Collection Protocol

All subjects were fitted with 68 optical reflective markers that were applied to anatomical landmarks as per a carefully designed protocol. Additionally 8 EMG electrodes were affixed to pertinent major muscle groups: bilateral pectoralis major, deltoids, latisimus dorsi, and triceps. Force sensing gloves were worn on left and right hands.

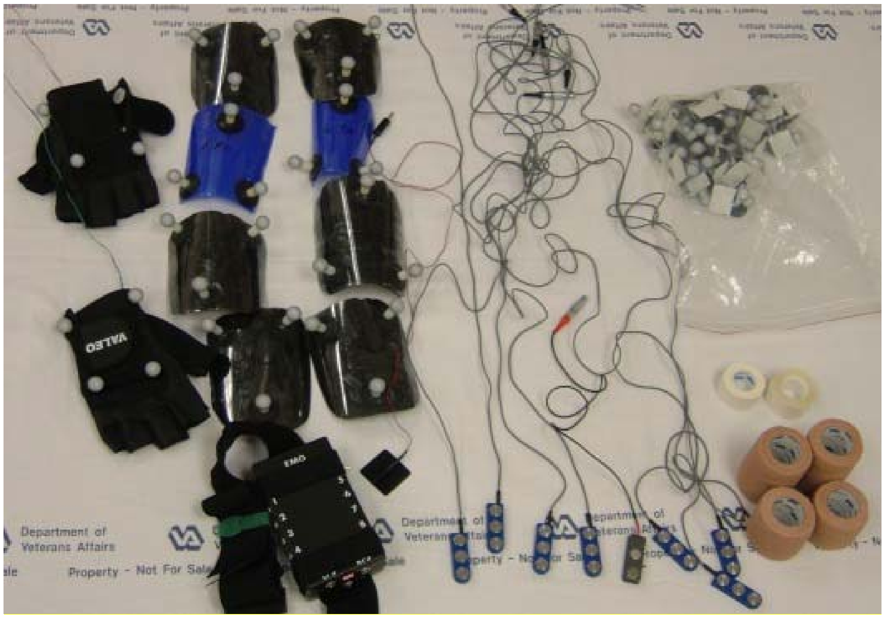

Figure 7. Data Collection Materials Worn by Participants

A data collection checklist was created to aid investigators in completing each of the complex data collection steps without error (Appendix H). Participants were asked to perform a series of independent activities. This included two stationary pressure relief tasks, one using the wheelchair armrests and one using the wheels, and three typical transfers between the standardized wheelchair and bed, commode, and vehicle. The order of task presentation was randomized (as per Appendix I). Data was collected using the Vicon motion capture system, EMG, and force gloves throughout task performance for subsequent analysis. After performing each task, the subjects were asked to verbally rate the extent of pain experience during the performance of each experiment task. A 5-minute period for rest and recovery was permitted between tasks.

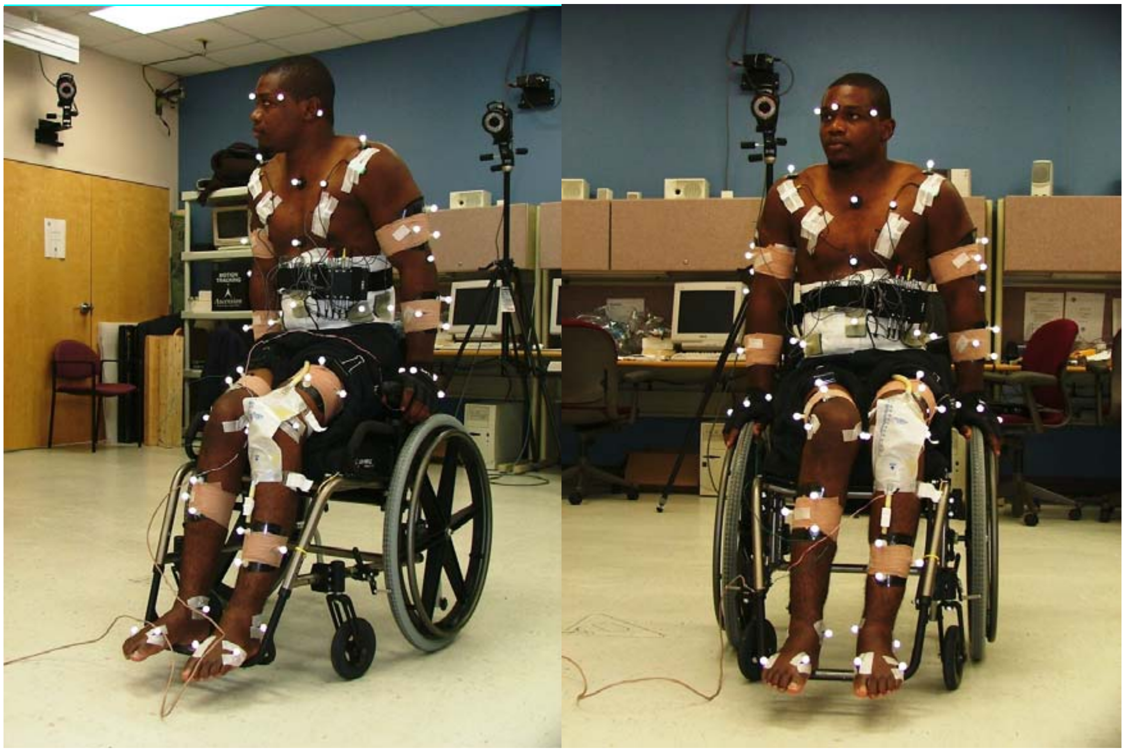

Figure 8. Pressure Relief: Armrest and Wheels

Two pressure reliefs were performed: one using the armrest and one using the wheels. The subject pressed on the armrest, lifted buttock off the seat, held this position for 3 seconds, and then lowered back into the seat. This same process was repeated using the wheelchair wheels.

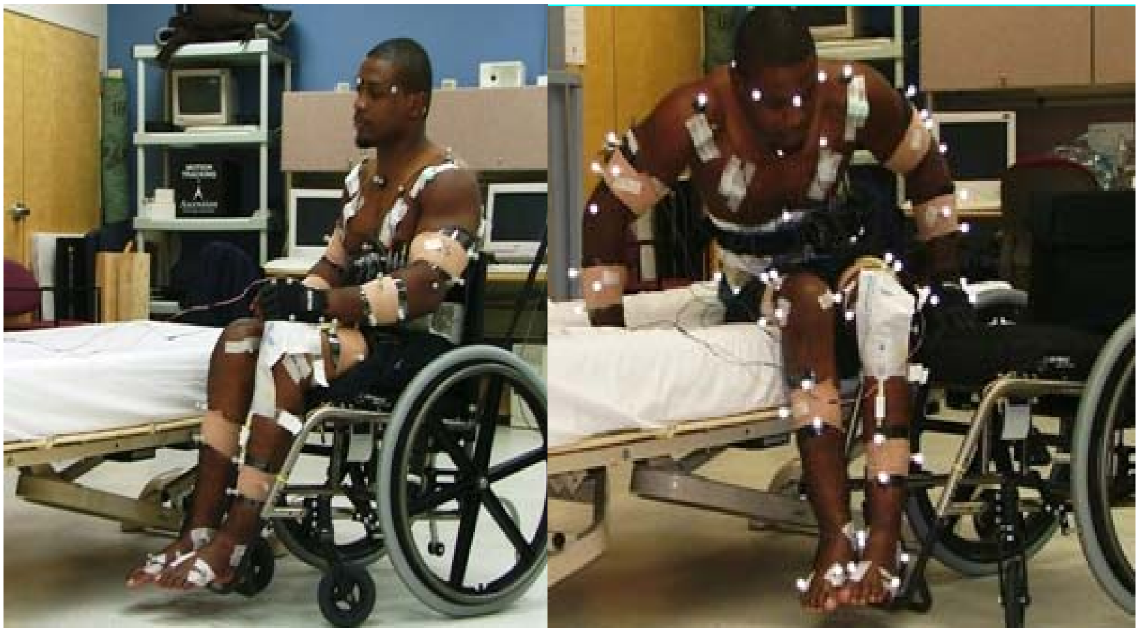

Figure 9. Transfer from Wheelchair to Bed and from Bed to Wheelchair

The subject transferred from a wheelchair to a bed, which was set at a distance of 45 cm. from the floor to the bed. The subject waited 10 seconds and transferred back into the wheelchair. The subjects used their dominant right arm as the leading arm to transfer to the bed. This transfer was to simulate a level transfer.

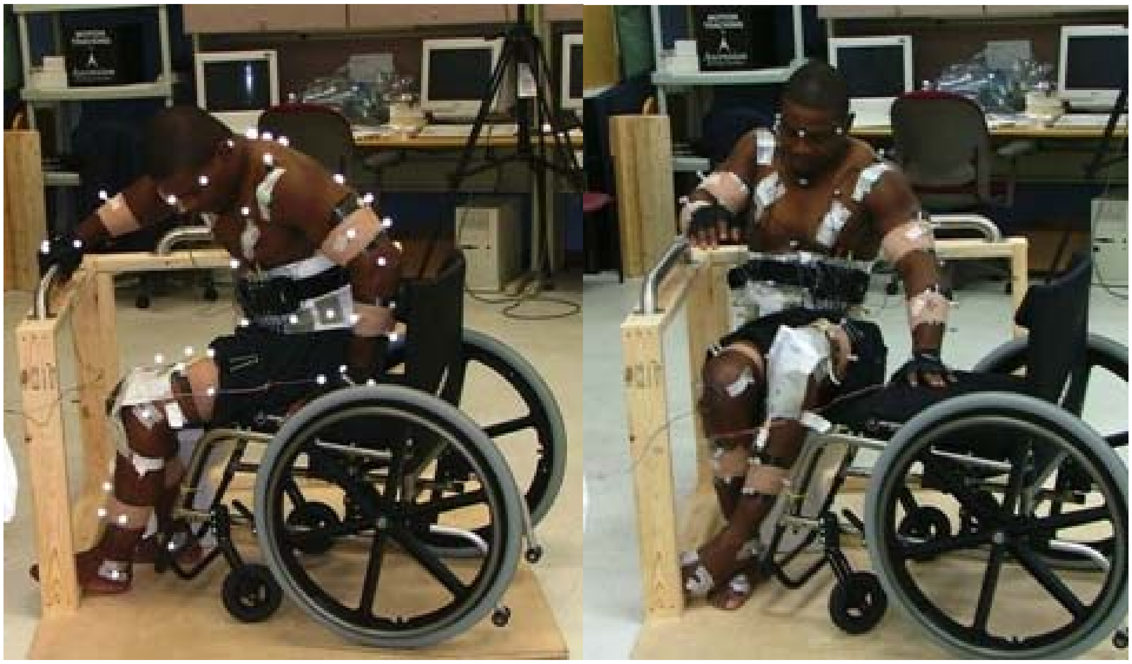

Figure 10. Transfer from Wheelchair to Toilet and Toilet to Wheelchair

The wheelchair seat was 45 cm to the ground. The toilet seat was 38 cm to the ground. The wheelchair was positioned at approximately 90° to the toilet. The position was to simulate the bathroom situation. The subject transferred using his dominant right arm as the leading arm. The subject transferred from the wheelchair to the toilet. For safety reasons the subject was allowed to use the grab bar or seat, and transfer at his own pace. After a 30 second rest the subject then transferred back to the wheelchair. The rest period was so short because the subjects wanted to spend as little time as possible on the toilet seat due to comfort reasons.

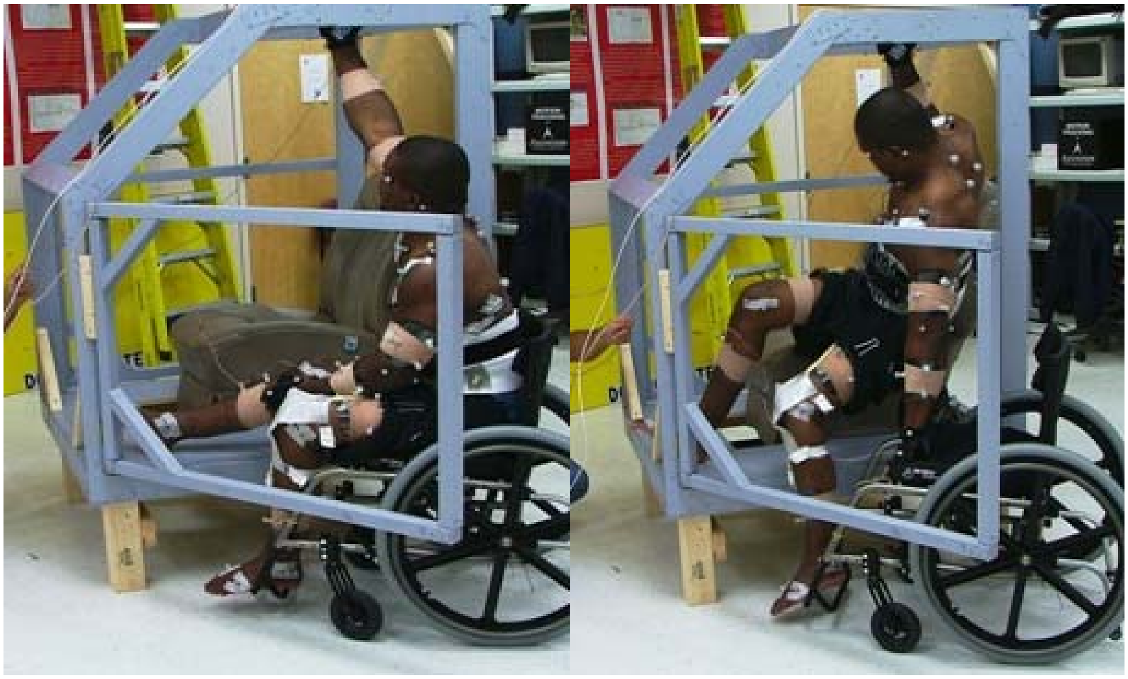

Figure 11. Transfer from Wheelchair to Vehicle Seat and Vehicle Seat to Wheelchair

The mock-up driver's seat was at a height of 58 cm above the ground.

The wheelchair was positioned as close to the seat as possible trying to simulate working around the door as an obstacle. The total horizontal distance to transfer was approximately 30 cm. The subject transferred at his own speed using the vehicle seat and the over head hand grip. The subject transferred using his right arm as the leading arm. After a 1 minute rest the subject transferred back into the wheelchair.

3.8 Data Management

Biomechanical analyses were applied to the model to compute joint angles, torques and moments acting on key body segments, such as the shoulders.

Electromyography recordings were referenced to a calibration measure so that muscle effort could be computed both as a direct force measurement and as a percentage of maximum voluntary contraction (MVC).

Objective findings were compiled and analyzed across participants to identify those components of the transfer tasks that imposed the greatest biomechanical stresses on the musculoskeletal system, in particular, the shoulders.

Chapter 4

Results

Table 1. Subject Anthropometric Measurements

Variable	Statistic
Weight (kg)	
M (SD)	74.7 (12.7) kg
Range	52-100 kg
Stature (mm)	
M (SD)	1744.8 (61.0) kg
Range	1651-1854 kg
Body Mass Index	
M (SD)	24.7 (4.2) kg
Range	19-33 kg
Note. M = Mean; SD = Standard Deviation;	
kg = kilograms; mm = millimeters.	

Table 2. Demographic Characteristics of Subjects

Variable		Statistic
Age		
	M (SD)	47.8 (11.1) yrs
	Range	21-57 yrs
Race		
	African-American	20.0%
	Caucasian	50.0%
	Hispanic	30.0%
SCI duration		
	M (SD)	22.7 (11.9) yrs
	Range	1-37 yrs
Level of injury		
	T2 - T6	60.0%
	T7 - T12	20.0%
	L1-L2	10.0%
Completeness		
	Incomplete	10.0%
	Complete	90.0%
Note. *M* = Mean; *SD* = Standard Deviation;		
SCI = spinal cord injury.		

Table 3. Shoulder Range of Motion and Strength of Subjects

		Left		Right	
Variable		Statistic			
		ROM (°)	Strength (lbs.)	ROM (°)	Strength (lbs.)
Flexion					
	M (SD)	166.0 (22.9)	12.7 (5.8) lbs	167.5 (17.6)	13.8 (6.4) lbs
	Range	125-180	2-22 lbs	133-180	2-27 lbs
Extension					
	M (SD)	49.3 (13.4)	14.6 (6.9) lbs	53.1 (15.5)	15.2 (6.8) lbs
	Range	23-65	6-25 lbs	16-66	5-24 lbs
Abduction					
	M (SD)	163.3 (28.0)	14.5 (6.9) lbs	164.8 (23.0)	14.6 (6.2) lbs
	Range	100-180	2-27 lbs	125-180	7-27 lbs
External rotation					
	M (SD)	78.5 (19.2)	6.4 (3.0) lbs	81.1 (17.1)	5.9 (3.3) lbs
	Range	42-90	3-13 lbs	48-90	1-10 lbs

Note. ROM = range of motion; *M* = Mean; *SD* = Standard Deviation.

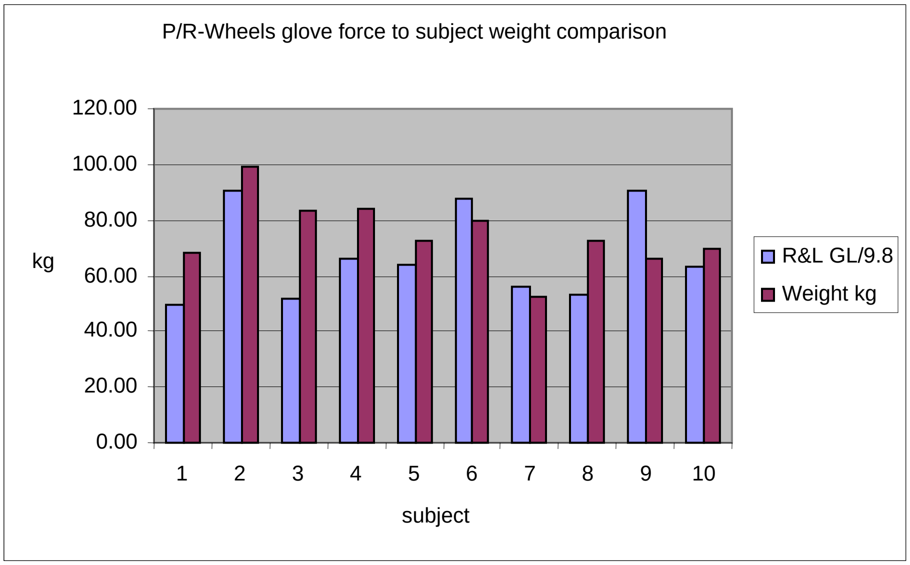

Figure 12. Pressure Relief Wheels Glove Force to Subject Weight Comparison

This measurement (pressure relief wheels glove force) was a check to see if the subjects were squeezing with their hands, thus applying more force than just their body weight. The subject's mean force data for a 3 second time interval was used to allow for the initial spike in force needed to lift the subject to the appropriate height. Seven subject's weights were greater than the force at their gloves, which is what was desired. Subjects 6 and 7 had forces slightly greater than their body weight, and subject 9 had a 38 % greater force at his glove than his bodyweight. Subject 9 was squeezing much more than the other subjects.

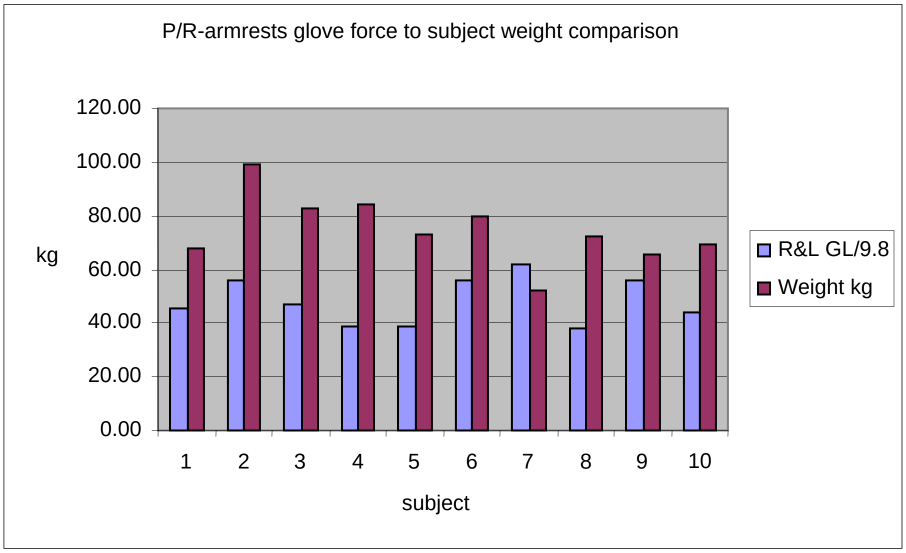

Figure 13. Pressure Relief Armrest Glove Force to Subject Weight Comparison

This measurement (pressure relief armrest glove force) was also a check to see if the subjects were squeezing with their hands, thus applying more force than just their body weight. This pressure relief reading was much better. The bodyweights were approximately 50% higher than the forces at the gloves. Only subject 7 had a force 17 % higher than his bodyweight, so was still squeezing with his hands.

Table 4. Pressure Relief Comparison

	Max L Shoulder Force N	Max R Shoulder Force N	Total Max Shoulder Force N	Mean L Shoulder Force N	Mean R Shoulder Force N	Total Mean Shoulder Force N
P/R Wheels	633.41	376.21	1009.62	377.56	180.42	557.98
P/R Armrest	320.65	402.09	722.74	192.63	185.65	378.28
Totals	954.06	778.3		570.19	366.07	
	Max L Shoulder Torque N	Max R Shoulder Torque N	Total Max Shoulder Torque N	Mean L Shoulder Torque N	Mean R Shoulder Torque N	Total Mean Shoulder Torque N
P/R Wheels	45867.08	19023.64	64890.72	6238.84	8328.46	14567.3
P/R Armrest	15700.51	16002.36	31702.87	3810.24	8207.09	12017.33
Totals	61567.59	35026		10049.08	16535.55	
	Mean Shoulder work Nmm					
P/R Wheels	205					
P/R Armrest	254					

During the P/R using the wheels there was a 40% greater max shoulder force and a 47% greater mean shoulder force than when using the armrest. The max shoulder force of over 1000 N was generated at the initial push off, during a P/R using the wheels, then the force dropped 45% to an average of 558 N. The max shoulder force of 722 N at the initial push off, during a P/R, using the Armrest, dropped 48% and then averaged 378 N.

During the P/R using the wheels there was a 104% greater max shoulder torque and a 17% greater mean shoulder torque than when using the armrest. As in the initial large amount of shoulder force there was also a large amount of shoulder torque that dropped 77% during the P/R using the wheels. The shoulder torque decreased 62% during the P/R using the armrest. Because of the greater distance the body's Center of Mass (COM) traveled during the P/R using the armrest, 24% more work was done.

During the P/R using the wheels, the subjects' mean shoulder force on the left side was 110% greater than the right side mean shoulder force. The P/R using the armrests was approximately even.

During the P/R using the wheels, the torque on the right shoulder was 34% greater than on the left shoulder. During the P/R using the armrests, the right side torque was 115% greater than the left side torque.

Table 5. Subject's Hand Position for Data Collection

Patient		w/c to bed	w/c to commode	Pressure Relief – wheels	Pressure Relief - armrests
2 Sub 1	Kinematics	X	Ok	ok	X
	Kinetics	X	X	X	X
	LGlove F	ok	Ok	ok	ok
	RGlove F	ok	ok	ok	ok
	LHand	ok	ok	ok	ok
	RHand	ok	ok	ok	ok
3 Sub 2	Kinematics	X	X	X	X
	Kinetics	ok	ok	ok	ok
	LGlove F	LOW	ok	ok	ok
	RGlove F	LOW	ok	ok	ok
	LHand	KNUCKLES	ok	ok	ok
	RHand	FINGERTIPS	ok	ok	ok
4 Sub 3	Kinematics	X	X	ok	X
	Kinetics	ok	ok	ok	ok
	LGlove F	ok	LOW	ok	ok
	RGlove F	UNFILTERED?	ok	ok	ok
	LHand	ok	FINGERTIPS	ok	ok
	RHand	KNUCKLES	ok	ok	ok
5 Sub 4	Kinematics	X	X	X	X
	Kinetics	ok	ok	ok	ok
	LGlove F	ok	LOW	ok	ok
	RGlove F	ok	ok	ok	ok
	LHand	ok	ok	ok	ok
	RHand	ok	ok	ok	ok
6 Sub 5	Kinematics	X	X	X	ok
	Kinetics	RSIDE – Y AXIS	L&R MISSING SOME DATA	ok	ok
	LGlove F	ok	ok	ok	ok
	RGlove F	X	X	ok	ok
	LHand	ok	ok	ok	ok
	RHand	KNUCKLES	ok	ok	ok
7 Sub 6	Kinematics	X	X	ok	ok
	Kinetics	ok	NO DATA	ok	ok
	LGlove F	ok	ok	ok	ok
	RGlove F	NOISY	ok	ok	ok
	LHand	ok	ok	ok	ok
	RHand	KNUCKLES	ok	ok	ok

Table 5. (Continued)

8 Sub 7	Kinematics	X	X	ok	ok
	Kinetics	ok	ok	ok	ok
	LGlove F	ok	ok	ok	ok
	RGlove F	LOW	ok	ok	ok
	LHand	ok	ok	ok	ok
	RHand	KNUCKLES	ok	ok	ok
9 Sub 9	Kinematics	X	X	ok	X
	Kinetics	ok	ok	ok	ok
	LGlove F	ok	ok	ok	ok
	RGlove F	ok	HIGH	ok	ok
	LHand	KNUCKLES	ok	ok	ok
	RHand	ok	Ok – tight grip	ok	ok
10 Sub 10	Kinematics	x	NO DATA	ok	x
	Kinetics	ok	NO DATA	ok	ok
	LGlove F	ok	NO DATA	ok	ok
	RGlove F	ok	NO DATA	ok	ok
	LHand	KNUCKLES	NO DATA	ok	ok
	RHand	KNUCKLES	NO DATA	ok	ok
11 Sub 8	Kinematics	x	x	ok	x
	Kinetics	ok	ok	ok	ok
	LGlove F	ok	ok	ok	ok
	RGlove F	ok	ok	ok	ok
	LHand	KNUCKLES	ok	ok	ok
	RHand	ok	ok	ok	ok

X = false reading

Transfer data and EMG data were not able to be reported due to reasons that are discussed in section 5.1 (Limitations of Laboratory Devices and Equipment and the Recommended Changes.)

Chapter 5

Discussion

5.1 Limitations of Laboratory Devices and Equipment and the Recommended Changes

Since this was a pilot study attempting to use the Tekscan pads and the gloves, there was no information available to indicate how durable they were. It was found that they varied in durability, and had to be replaced numerous times throughout the study. The force pads had to be hardwired with a 22 gauge wire as wireless was not possible. The data processing could not be viewed in real-time. All the data had to be gathered before the results could be calculated and any decisions could be made. The data processing included the motion analysis data, the force data, and the EMG data.

The computers used in this study, which were state-of-the-art at the time, could not easily handle trials of extended length. At best this was an inconvenience, but at worst certain trials could not even be opened after they were recorded. The capabilities of the 6-camera Vicon 460 Motion Analysis System used in this study were such that the automatic marker labeling function worked correctly for the lower extremities but did not work correctly for the upper-body. This necessitated the time-consuming task of manually labeling every trial. Complicating the task of manual labeling was the problem of the impaired marker visibility. With only six cameras, at least two of which are required to resolve the marker positions, marker positions were often obscured. Markers were difficult to label accurately when they disappeared and reappeared. Furthermore, when enough markers were not visible, the kinematics and kinetics could not be calculated. The wheelchair-vehicle transfers, while the most interesting to examine, were also the most difficult for which to obtain adequate data. The wide cross-section of the wooden 2x4s used to construct the vehicle mock-up obscured most of the markers during the trial. For future studies, a new vehicle mock-up should be built out of metal tubing with a much smaller cross-sectional area that would allow the recording of Vicon data without obscuring the markers.

The marker resolving problems encountered during this study suggest that a 12-camera Vicon MX system should be used in future studies. This new system should be able to resolve markers more accurately and reliably and should be able to auto-label more reliably than the 6-camera Vicon 460 system used for this study. The superior capabilities of this system should permit accurate data to be collected for all tasks and should require far less time for post-processing. The Vicon MX system comes with an upgraded computer system that can handle all the anticipated processing needs.

The force-detecting gloves worked well for simple tasks such as pressure relief, but performed inadequately for other tasks due to the following unforeseen complications:

- Surface of the hand was not always used. The subjects often preferred their fingertips or knuckles (which were not instrumented) to the palm of the hand (which was instrumented).
- Direction of the force vector could not be accurately determined with single sensor force gloves. This may have resulted in inaccurate kinetics.
- Resistive sensors broke down with repeated use and did not measure forces accurately. Gloves that incorporate force sensors capable of meeting the demand of repeated use should be used in the future.
- Load cells were not present. Load cells should be used in newly designed devices, to supplement force data.

With the advent of the new LifeMod program, from Vicon Motion Analysis, forces and torques may be calculated using only motion capture.

The EMG system used in this study presented problems including poor data communication through telemetry, the reference electrode positioning may not have been electrically neutral and may have biased the data, and the MVC tasks were not similar enough to functional motions utilized for the transfers. The specific direction and speed (static) of the muscle contraction during the MVC trial did not necessarily correspond to the orientation and speed (dynamic) of the muscle during the trials. A wired 16-channel EMG system should be utilized in future studies which would resolve these technological issues and allow accurate EMG data to be obtained. Another option would be to record MVCs while a subject is performing a maximum repetition in a custom made device that incorporates a load cell and matches the task to be performed as closely as possible.

5.2 Discussion

Under the original guidelines, this wheelchair study was to be completed in a one-year time frame. The VA was planning to purchase the Vicon 460 Motion Analysis System by March of 2003. Due to purchasing constraints the Vicon system was installed in October of 2003. The purchaser, Dr. John Lloyd of the VA, was told that the Vicon software would process the input data and produce the force, moments, and torques necessary to do a complete biomechanical analysis. But, in actuality, the software was structured mainly for gait analysis. The upper body, specifically the shoulder joint, was too complicated for the software program that had been supplied. To complicate matters further, the subjects were in wheelchairs, which blocked the markers from the cameras. Dr. Lloyd spent the next six months rewriting the supplied program while this researcher worked on new markers and triads that would allow us to capture the necessary body parts. Because of this time delay it was decided to add a transfer into a vehicle seat, which it was believed would simulate the most stressful transfer that a paraplegic would encounter during the course of a day.

The subjects from the pool of VA paraplegics in Tampa, Florida were to be supplied by a physician in the spinal cord injury department. Due to unforeseen circumstances this researcher had to take over this task. Instead of gathering data in June of 2004 as originally planned, the months of June and July were spent obtaining subjects. The actual data gathering started in September of 2004. Since the original timeline for this study had September of 2004 as the completion date, extensions were submitted.

Transfers out of the wheelchair took over 6 times longer than anticipated and it required twice as many hand positions than the transfers back into the chair. Among subjects there was an immense amount of variability in time and number of hand positions required for the transfers. Across all subjects for the identical transfer, the standard deviation of the time required was 118% of the mean and the standard deviation of the number of hand positions was 56% of the mean. A possible reason for this may have been that the wheelchair users tested appeared to be very cautious in transferring to unknown surfaces. This was observed by noting the multiple hand placements used before the subject felt comfortable enough to begin the transfer.

The pressure reliefs were the best examples in the data gathering experiments. The limitations on the force gloves were still evident, but not as noticeable as in the transfers. The most useful readings were obtained from pressure reliefs performed using the armrest. The subjects were able to keep their hands relatively flat on the armrest. When subjects used the wheels for the pressure relief, the tendency to grab the wheel was higher, probably due to a smaller round surface that was easier to grasp and was further away from the body. The peak shoulder forces when performing a pressure relief were approximately 40% higher using the wheels then when using the armrests. The peak shoulder torques when performing a pressure relief using the wheels were 100% greater than when using the armrest. There was a large difference when comparing right shoulder to left shoulder. When performing the P/R using the wheels the right was 34% greater than the left. When performing the P/R using the armrest the right was 115% greater than the left. The reason why the right shoulder has a higher torque value than the left shoulder is not clear. There is a possibility the right glove data was not accurate. Further study on this issue is needed.

Work performed during seated pressure reliefs using the armrests was 24% greater than when using the wheels, due to greater distance through which the center of mass (COM) was moved. While pressure relief using the wheels may seem easier to patients due to a reduced workload, pressure relief using the armrests is preferred for long-term use, as joint forces and torques are lower at the shoulder, elbow and wrist. It is beneficial to keep the arms as close to the body as possible, such as when using the armrests, which reduces joint torques. Thus, the risk of injury due to cumulative trauma would be expected to be lower for pressure relief using the armrests than for pressure relief using the wheels. However, a design modification to the wheelchair armrests that allows them to drop down to a height sufficient enough to allow the user to clear their buttocks off the seat for pressure relief should provide the benefits of both reduced workload and lower peak forces and torques.

The vehicle transfers, in general, took more than twice as long and required almost twice as many hand positions as the other transfers. This was due to a number of factors -- the vehicle seat was 20 cm higher than the wheelchair seat resulting in an “uphill” transfer (no height difference for other transfers); the horizontal distance to the seat from the wheelchair was relatively large at approximately 30 cm; subjects could not use anything on the vehicle door as a handhold, since it was not structurally as sound as a real vehicle door; and the mockup had no steering wheel, which many subjects said they use for transfers into and out of vehicles. It was observed that the three individuals with the greatest muscular strength in relation to their body mass could more easily lift their bodies up into the vehicle seat compared to the difficult experience of the other subjects. These three stronger subjects regularly participate in weight training programs. The importance of training and diet are especially important for SCI patients who place high demands on their UE's during ADL's. The strength needed is reduced as mass is reduced, if greater strength is present then more mass can be lifted or transferred. The difficulty of these transfers indicates a need for better technology to assist the wheelchair user to get into and out of a vehicle. Existing technologies include slide boards and vehicle lifts, which require a sling and works similar to that of a floor based lift. A vehicle lift does not allow for independent vehicle transfers, as assistance is needed to bring the lift to the vehicle. Vehicle seats are also available which rotate out allowing the wheelchair user to safely transfer independently. Perhaps a consideration for addressing uphill transfers may be to design base wheelchairs so that they are height adjustable and could be raised to the level of the vehicle, facilitating an easier and quicker transfer for wheelchair dependent patients. Future studies are needed to evaluate technologies for vehicle ingress and egress, and how much muscular strength in relation to body composition are factors for a patient to safely transfer into a vehicle if no assistive devices are available.

When subjects transferred from the wheelchair to the commode they used the grab bar more often than the seat. While the grab bar is a more secure and safe handhold for immediate use, its position and distance from the subject's body required more effort by the subject. The reach necessary imposed greater stress on the active shoulder joint. The strain to the shoulder is similar to a gymnast performing an iron cross on the rings, and these subjects were no gymnasts. The subjects that attempted this transfer by using the commode seat rather than the grab bars were more able and confident in their abilities and likely perceived the threat to their hand slipping off the seat edge or the seat breaking under the hand forces to be minimal.

Results indicate that grasping the commode seat instead of the grab bar may be biomechanically preferable, although unconventional practice for public washrooms. These results indicate that the grab bar may actually be more dangerous in terms of long term cumulative trauma injury, but further research in this area is required to verify this. By using the toilet seat, the patient reduces shoulder torque by keeping the arms as close to the torso as possible. A potential solution may be in the design of handles for the commode. Two handles could be provided in the front of the bowl at approximately 50 degrees from the center of the bowl, one handle on each side. These handles would need to be strong enough to accommodate a person's bodyweight. The handles could be built into the seat so as to enable retro fitting toilets that are already in place.

Patients should be trained on the best technique to transfer from a wheelchair to a bed. The patient will then usually adopt the best transfer technique depending on their functional ability and strength. Strength training should be performed with all new wheelchair dependent patients to develop muscles key in transfers. These muscle groups are pectoralis major, trapezius, biceps and triceps, post/anterior deltoids, and rhomboids. Strengthening these muscles in new wheelchair users will prepare them to perform wheelchair transfers easier and safer. Training should be facilitated with and without an assistive device and patients should practice both methods.

Another factor that makes wheelchair to bed transfers challenging is transferring to specialty mattresses. Some mattresses' air features make hand placement difficult and uneven, thus creating an unstable surface to use for support. To solve this issue, there is a feature available called perimeter edge or bolster on mattresses, which provide a firm surface facilitating an easier lateral transfer. This feature is commercially available. Another option would be to inflate the mattress to its maximum setting so that the entire surface becomes as firm as possible prior to performing the transfer.

Chapter 6

Conclusions

6.1 Significance of this Study

A lot of information during this study came from observing the subjects while trying to perform the transfer and pressure relief tasks. The transfers in descending order from the most demanding to the least demanding were as follows: vehicle, commode, and bed. The subjects were able to perform pressure relief tasks with minimal effort even though some of the forces and torques, especially pressure relief using wheels, were considerably higher than using armrests. It seems that the key element is to keep the task as close to a linear, single plane activity as possible. The reaching out away from the body while twisting and trying to lift or lower oneself (abduction, adduction, internal and external rotation of the humerus) makes it very easy to go past the capabilities of the individual. The pressure relief task, if done properly, while having some high forces, could actually be beneficial as a strengthening tool for the shoulder, chest, and tricep muscles. If one's body mass or lack of strength prevents the pressure relief from being performed, then the individual cannot perform a transfer without risk of injury. The subjects who weight trained regularly were able to easily perform the pressure relief tasks and while more difficult, could do all the transfers.

6.2 Future Work

It is very difficult to capture a paraplegic individual during the course of a transfer. To use a motion capture system such as the Vicon 460, it would be necessary to eliminate the marker occlusion problem. This could be done by increasing to a 10-camera system and also by constructing the van or vehicle simulator using small .5 inch tubular steel that reduces the diameter of the support structure by 95 %.

An instrumented steering wheel that could capture forces would be of great benefit since all of the subjects stated that they use the steering wheel to help them transfer into the vehicle.

Brian Schulz, Ph.D., at the V.A. has been researching alternatives to the Tekscan force sensors. One technology that was found promising was the Quantum tunneling composites (QTC) which are available in 5 and 13 mm circles and 40 mm squares, but custom sizes are available. The company claims "significant benefits over existing technologies, in reliability, ruggedness, flexibility and cost". Multiple sensors on the palmar surface of the hand should be used to quantify gripping forces from opposing digits. The knuckle sensor is required because prior research has shown that a closed hand posture is utilized during various independent transfer tasks.

A future study should compare the strength training component in two groups of SCI wheelchair users to observe if there is a significant benefit. Both groups of users would be taught similar technique in terms of how to safely transfer out of a wheelchair, but the experimental group would receive additional strength training on key muscles groups in addition to technique. This study design will benefit and may potentially affect the rehabilitative component of SCI patients at early onset of injury.

Measuring an individual’s strength, relative to body mass, and endurance would help to better know what the shoulder, chest, and arm soft tissue limits are when lifting and transferring bodyweight many times throughout the day. A possible question to study would be -- are pressure reliefs detrimental or can they be used as a training aid?

With the advent of the new LifeMod program, forces and torques are able to be calculated using only motion capture. After observing the varied difficulty levels during all tasks, the benefit of knowing the strength and flexibility of a subject, in relation to their body mass, would benefit the patient and the therapist. Measuring the patient’s strength both statically and dynamically with a Biodex or similar piece of equipment would be useful, to have a baseline to which to compare the forces and moments. Tissue damage occurs when it is subjected to a certain loading threshold. As one trains and gets stronger, this loading threshold increases. Not only do the thresholds for muscle and ligament damage increase, but work load capacity also increases. The increased work load capacity decreases the fatigue factor -- muscle fatigue is a gradual linear reduction of muscular force generating capacity, which is a result of inadequate muscle recovery time. When muscles are fatigued and can no longer contract or function properly, other muscles must now be utilized, that can lead to injury because of a task being performed improperly. Concentrating on these areas can also improve overall health and build self confidence.

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Appendices

Appendix A. Manual Muscle Testing

SUBJ# _____

Name: ________________________________

Date: ______/______/2004

Table 6. Manual Muscle Testing Data

Muscle group	Action	MMT1 (kg)	MMT2 (kg)	MMT3 (kg)	Pain Score (0-10)
Left Scapula	Elevation				
	Depression				
	Protraction				
	Retraction				
Right Scapula	Elevation				
	Depression				
	Protraction				
	Retraction				
Left Glenohumeral	Flexion				
	Extension				
	Abduction				
	Adduction				
	Ext rotation				
	Int rotation				
Right Glenohumeral	Flexion				

Appendix A. (Continued)

Table 6. (Continued)

	Extension				
	Abduction				
	Adduction				
	Ext rotation				
	Int rotation				
Right elbow	Flexion				
	Extension				
Left elbow	Flexion				
	Extension				
Left wrist	Extension				
Right wrist	Extension				
LHand Power Grip	Flexion				
RHand Power Grip	Flexion				

Appendix B. Active Range of Motion Testing

SUBJ# _____

Name: ________________________________

Date: ______/______/2004

Table 7. Active Range of Motion Testing Dada

Location	AROM	Measure (degrees)	Deficit (comp to norm)	Pain (0-10)
Left Shoulder	Flexion			
	Extension			
	Abduction			
	Adduction			
	Internal rotation			
	External rotation			
Right Shoulder	Flexion			
	Extension			
	Abduction			
	Adduction			
	Internal rotation			
	External rotation			

Appendix C. FABQ-P

SUBJ# _____

Name: ______________________________

Date: ______/______/2004

Here are some of the things which other patients have told us about their pain. For each statement, please circle any number from 0 to 4 to say how much physical activities such as bending, lifting, walking or driving affect or would affect your back pain.

1. Physical activity makes my pain worse 0 1 2 3 4
NA

2. Physical activity might harm me 0 1 2 3 4
NA

3. I should not do physical activities which
(might) make my pain worse 0 1 2 3 4
NA

4. I cannot do physical activities which
(might) make my pain worse 0 1 2 3 4
NA

Appendix D. Physician Evaluation

SUBJ# _____

Name: ________________________________

Date: _____/_____/2004

Table 8. Physician Evaluation Data

	Acceptable	Unacceptable
Informed Consent		
Demographic Questionnaire		
Health Questionnaire		
Pain Rating Scale		
Review from medical file:		
Medications		
ASIA level		
Cardiac:		
Pulmonary:		
Peripheral vascular		
Endocrine		
Rheumatology		
PT: Anthropometry Survey		
PT: Range-of-Motion Testing		
PT: Manual Muscle Testing		

Appendix D. (Continued)

Table 8. (Continued)

After evaluating the subject's history and pertinent physical findings, this subject may safely participate in the wheelchair transfer study.	Signature of physician: Date:
Subject not recommended for participation. Reason:	Signature of physician: Date:

Appendix E. Demographic Questionnaire

SUBJ# _____

Name: ______________________________
Date: _____/_____/2004

Age: __________ yrs.

Gender: Male / Female (please circle)

Race (please circle): White / African American / Asian / Hispanic / Native American / Other

Dominant Hand (please circle): Left / Right

Are you a smoker (please circle)? Yes / No
If Yes, please indicate: [Light (1-5 /day); Medium(5-20 /day); Heavy (20+/day)]

What is your occupation? ____

What physical activities does your job involve?
____
____
____

What leisure / recreational activities do you pursue? How often?
____
____
____

Appendix F. Health Questionnaire

SUBJ# _____

Name: ________________________________ Date:____________
_____/_____/2004

What is the level of your Spinal Cord Injury?

____

Is your injury: Complete or Incomplete (please circle)
What is the duration since initial injury?

____

Have you developed any secondary conditions?

____

____

Any current or recent decubitus ulcers / pressure sores? YES / NO (please circle) If Yes, please describe:

____

Any current or recent Upper Extremity injuries or surgeries? YES / NO (please circle) If Yes, please describe:

____

What medications are you presently taking?

____

____

Appendix G. Anthropometry Survey

SUBJ# _____

Name: ____

Date: ______/______/2004

Table 9. Anthropometry Survey Data

Anthropometry Measures			
1	Weight (ask)	kg	lb
2	Stature (ask)	mm	ft/in
3	Body Mass Index (calculated)		
4	Abdominal Depth	mm	in
5	Inter-Asis Distance	mm	in
6	Upper Leg Length (popliteal to trochanter)	mm	in
7	Lower Leg Length (ankle to popliteal)	mm	in
8	Footrest to Popliteal height (no shoe)	mm	in
9	Hand length (fingertip to wrist crease)	mm	in
10	Hand Thickness	mm	in

Appendix H. Data Collection Protocol Checklist

Table 10. Data Collection Protocol Checklist

Check	Item	Time/min
	Informed Consent	15
	Demographic Questionnaire	5
	Health Questionnaire	5
	Pain Rating Scale	5
	Anthropometry Survey	10
	Range-of-Motion Testing	20
	Manual Muscle Testing	20
	Evaluation subtotal	80 min
	Restroom break	
	Recycle all power – Vicon computer, Desktop computer, camera, EMG, A/D Power Supply	2
	Calibrate Vicon system	15
	Install EMG Telemetry pack	3
	Install EMG Electrodes: 1&2=L/R Anterior Deltoid; 3&4=L/R Pectoralis Major; 5&6=Lattisimus Dorsi; 7&8=L/R Triceps; [Alt 7&8=L/r Biceps for Trapeze]	10
	Install Vicon Triads	15
	Last chance for restroom break	
	Install Gloves	5
	Install Markers	30
	Vicon setup subtotal	80 min
	Static Vicon Data Capture – Laying	5
	Static Vicon Data Capture: 0,120,240 degrees	5
	MVC: in order as presented above	15
	Transfers (order randomized as per following table)	
	Pressure Relief Task (using wheelchair wheels)	5
	Pressure Relief Task (using wheelchair armrests)	5

Table 10. (Continued)

	Wheelchair to Bed / Bed to Wheelchair	15
	Wheelchair to Vehicle / Vehicle to Wheelchair	15
	Wheelchair to Commode / Commode to Wheelchair	15
	Switch EMG electrodes 7&8 (L/R Triceps) to Alt 7&8 (L/R Biceps)	5
	MVC: L/R Biceps	5
	Transfer to Bed in Supine position (not evaluated)	5
	Repositioning using Trapeze Bar: 2-handed; 1-handed (dominant side)	10
	Data collection subtotal	105 min
	TOTAL	200 min

Appendix I. Order of Transfer Tasks

Table 11. Order of Transfer Tasks

	Task1	Task2	Task3
Subject 0	Vehicle	Bed	Commode
Subject 1	Bed	Vehicle	Commode
Subject 2	Bed	Commode	Vehicle
Subject 3	Commode	Vehicle	Bed
Subject 4	Commode	Bed	Vehicle
Subject 5	Commode	Vehicle	Bed
Subject 6	Vehicle	Bed	Commode
Subject 7	Commode	Vehicle	Bed
Subject 8	Vehicle	Bed	Commode
Subject 9	Bed	Commode	Vehicle
Subject 10	Vehicle	Commode	Bed
Subject 11	Bed	Commode	Vehicle

Appendix J. Vicon BodyBuilder Program

```
!MKR#2

[Autolabel]
GLAB Glabellum
LTEM Left Temple
RTEM Right Temple
LMAS Left Mastoid Process
RMAS Right Mastoid Process

CSPN C7 Posterior vertebral prominance
CLAV Clavicle
STRN Sternum
CHST (Optional Asymmetry Marker)

LSCS Left Scapula Superior Prominence
LSCI Left Scapula Inferior Prominence
RSCS Right Scapula Superior Prominence
RSCI Right Scapula Inferior Prominence

LACR Left Acromium
LHT1 Left Humerus Triad Marker 1
LHT2 Left Humerus Triad Marker 2
LHT3 Left Humerus Triad Marker 3

LELB Left Lateral Elbow
LMEL Left Medial Elbow
LRT1 Left Radius Triad Marker 1
LRT2 Left Radius Triad Marker 2
LRT3 Left Radius Triad Marker 3

LRAD Left Radius
LULN Left Ulnar
LFIN Left Hand 2nd Meta-Carpal
LLFI Left Hand 5th Meta-Carpal

RACR Right Acromium
RHT1 Right Humerus Triad Marker 1
RHT2 Right Humerus Triad Marker 2
RHT3 Right Humerus Triad Marker 3
```

Appendix J. (Continued)

RELB	Right Lateral Elbow
RMEL	Right Medial Elbow
RRT1	Right Radius Triad Marker 1
RRT2	Right Radius Triad Marker 2
RRT3	Right Radius Triad Marker 3
RRAD	Right Radius
RULN	Right Ulnar
RFIN	Right Hand 2nd Meta-Carpal
RLFI	Right Hand 5th Meta-Carpal
MPEL	Mid-Pelvis
LASI	Left Anterior Illiac Spine
RASI	Right Anterior Illiac Spine
LSIS	Left Superior Illiac Spine
RSIS	Right Superior Illiac Spine
LFT1	Left Femur Triad Marker 1
LFT2	Left Femur Triad Marker 2
LFT3	Left Femur Triad Marker 3
LKNE	Left Lateral Knee
LMKN	Left Medial Knee
LTT1	Left Tibia Triad Marker 1
LTT2	Left Tibia Triad Marker 2
LTT3	Left Tibia Triad Marker 3
LANK	Left Ankle
LMAN	Left Medial Ankle
LTOE	Left Foot 2nd Meta-Tarsal
LLTO	Left Foot 5th Meta-Tarsal
RFT1	Right Femur Triad Marker 1
RFT2	Right Femur Triad Marker 2
RFT3	Right Femur Triad Marker 3
RKNE	Right Lateral Knee
RMKN	Right Medial Knee
RTT1	Right Tibia Triad Marker 1
RTT2	Right Tibia Triad Marker 2
RTT3	Right Tibia Triad Marker 3
RANK	Right Ankle
RMAN	Right Medial Ankle

Appendix J. (Continued)

```
RTOE Right Foot 2nd Meta-Tarsal
RLTO Right Foot 5th Meta-Tarsal
Head                = GLAB,LTEM,RTEM,LMAS,RMAS
Thorax                      = CSPN,CLAV,STRN,LACR,RACR,CHST
Abdomen             = STRN,LASI,RASI
LeftScapula         = LACR,LSCS,LSCI
RightScapula        = RACR,RSCS,RSCI
Pelvis              = MPEL,LASI,RASI,LSIS,RSIS
LeftHumerus         = LACR,LELB,LMEL,LHT1,LHT2,LHT3
LeftRadius          = LELB,LMEL,LRAD,LULN,LRT1,LRT2,LRT3
LeftHand            = LRAD,LULN,LFIN,LLFI
RightHumerus                = RACR,RELB,RMEL,RHT1,RHT2,RHT3
RightRadius         = RELB,RMEL,RRAD,RULN,RRT1,RRT2,RRT3
RightHand           = RRAD,RULN,RFIN,RLFI
LeftFemur           = LASI,LSIS,LKNE,LMKN,LFT1,LFT2,LFT3
LeftTibia           = LKNE,LMKN,LANK,LMAN,LTT1,LTT2,LTT3
LeftFoot            = LANK,LMAN,LTOE,LLTO
RightFemur          = RASI,RSIS,RKNE,RMKN,RFT1,RFT2,RFT3
RightTibia          = RKNE,RMKN,RANK,RMAN,RTT1,RTT2,RTT3
RightFoot           = RANK,RMAN,RTOE,RLTO

Head,Thorax
Thorax,Abdomen
Abdomen,Pelvis
Thorax, LeftScapula
Thorax,LeftHumerus
LeftHumerus,LeftRadius
LeftRadius,LeftHand
Thorax, RightScapula
Thorax,RightHumerus
RightHumerus,RightRadius
RightRadius,RightHand
Pelvis,LeftFemur
LeftFemur,LeftTibia
LeftTibia,LeftFoot
Pelvis,RightFemur
RightFemur,RightTibia
RightTibia,RightFoot


[Axis Visualization]
ORIGINHead
AXISXHead
AXISYHead
```

AXISZHead
ORIGINHead,AXISXHead
ORIGINHead,AXISYHead
ORIGINHead,AXISZHead
ORIGINCSpine
AXISXCSpine
AXISYCSpine
AXISZCSpine
ORIGINCSpine,AXISXCSpine
ORIGINCSpine,AXISYCSpine
ORIGINCSpine,AXISZCSpine

ORIGINThorax
AXISXThorax
AXISYThorax
AXISZThorax
ORIGINThorax,AXISXThorax
ORIGINThorax,AXISYThorax
ORIGINThorax,AXISZThorax

ORIGINPelvis
AXISXPelvis
AXISYPelvis
AXISZPelvis
ORIGINPelvis,AXISXPelvis
ORIGINPelvis,AXISYPelvis
ORIGINPelvis,AXISZPelvis

ORIGINLClavicle
AXISXLClavicle
AXISYLClavicle
AXISZLClavicle
ORIGINLClavicle,AXISXLClavicle
ORIGINLClavicle,AXISYLClavicle
ORIGINLClavicle,AXISZLClavicle

ORIGINRClavicle
AXISXRClavicle
AXISYRClavicle
AXISZRClavicle
ORIGINRClavicle,AXISXRClavicle
ORIGINRClavicle,AXISYRClavicle
ORIGINRClavicle,AXISZRClavicle

Appendix J. (Continued)

ORIGINLScapula
AXISXLScapula
AXISYLScapula
AXISZLScapula
ORIGINLScapula,AXISXLScapula
ORIGINLScapula,AXISYLScapula
ORIGINLScapula,AXISZLScapula

ORIGINRScapula
AXISXRScapula
AXISYRScapula
AXISZRScapula
ORIGINRScapula,AXISXRScapula
ORIGINRScapula,AXISYRScapula
ORIGINRScapula,AXISZRScapula

ORIGINLHumerus
AXISXLHumerus
AXISYLHumerus
AXISZLHumerus
ORIGINLHumerus,AXISXLHumerus
ORIGINLHumerus,AXISYLHumerus
ORIGINLHumerus,AXISZLHumerus

ORIGINRHumerus
AXISXRHumerus
AXISYRHumerus
AXISZRHumerus
ORIGINRHumerus,AXISXRHumerus
ORIGINRHumerus,AXISYRHumerus
ORIGINRHumerus,AXISZRHumerus

ORIGINLRadius
AXISXLRadius
AXISYLRadius
AXISZLRadius
ORIGINLRadius,AXISXLRadius
ORIGINLRadius,AXISYLRadius
ORIGINLRadius,AXISZLRadius

ORIGINRRadius
AXISXRRadius
AXISYRRadius
AXISZRRadius

ORIGINRRadius,AXISXRRadius
ORIGINRRadius,AXISYRRadius
ORIGINRRadius,AXISZRRadius

ORIGINLHand
AXISXLHand
AXISYLHand
AXISZLHand
ORIGINLHand,AXISXLHand
ORIGINLHand,AXISYLHand
ORIGINLHand,AXISZLHand

ORIGINRHand
AXISXRHand
AXISYRHand
AXISZRHand
ORIGINRHand,AXISXRHand
ORIGINRHand,AXISYRHand
ORIGINRHand,AXISZRHand

ORIGINLFemur
AXISXLFemur
AXISYLFemur
AXISZLFemur
ORIGINLFemur,AXISXLFemur
ORIGINLFemur,AXISYLFemur
ORIGINLFemur,AXISZLFemur

ORIGINRFemur
AXISXRFemur
AXISYRFemur
AXISZRFemur
ORIGINRFemur,AXISXRFemur
ORIGINRFemur,AXISYRFemur
ORIGINRFemur,AXISZRFemur

ORIGINLTibia
AXISXLTibia
AXISYLTibia
AXISZLTibia
ORIGINLTibia,AXISXLTibia
ORIGINLTibia,AXISYLTibia
ORIGINLTibia,AXISZLTibia

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ORIGINRTibia
AXISXRTibia
AXISYRTibia
AXISZRTibia
ORIGINRTibia,AXISXRTibia
ORIGINRTibia,AXISYRTibia
ORIGINRTibia,AXISZRTibia

ORIGINLFoot
AXISXLFoot
AXISYLFoot
AXISZLFoot
ORIGINLFoot,AXISXLFoot
ORIGINLFoot,AXISYLFoot
ORIGINLFoot,AXISZLFoot

ORIGINRFoot
AXISXRFoot
AXISYRFoot
AXISZRFoot
ORIGINRFoot,AXISXRFoot
ORIGINRFoot,AXISYRFoot
ORIGINRFoot,AXISZRFoot


[Joint Centers]
LSJC  Left Shoulder Joint Center
RSJC  Right Shoulder Joint Center
LEJC  Left Elbow Joint Center
REJC  Right Elbow Joint Center
LWJC  Left Wrist Joint Center
RWJC  Right Wrist Joint Center
LFIN  Left ForeFinger
RFIN  Right ForeFinger
LHJC  Left Hip Joint Center
RHJC  Right Hip Joint Center
LKJC  Left Knee Joint Center
RKJC  Right Knee Joint Center
LAJC  Left Ankle Joint Center
RAJC  Right Ankle Joint Center
LSID  L5S1 Intervertebral Disc
LTOE  Left Toe
RTOE  Right Toe
```

LSJC,LEJC
LEJC,LWJC
LWJC,LFIN
RSJC,REJC
REJC,RWJC
RWJC,RFIN
LSJC,RSJC
LSJC,LSID
RSJC,LSID
LSID,LHJC
LSID,RHJC
LHJC,RHJC
LHJC,LKJC
LKJC,LAJC
LAJC,LTOE
RHJC,RKJC
RKJC,RAJC
RAJC,RTOE

[Centers of Mass]

HEDCM	Head CoM
THRCM	Thorax CoM
PELCM	Pelvis CoM
LHUCM	Left Humerus CoM
RHUCM	Right Humerus CoM
LRACM	Left Radius CoM
RRACM	Right Radius CoM
LHACM	Left Hand CoM
RHACM	Right Hand CoM
LFECM	Left Femur CoM
RFECM	Right Femur CoM
LTICM	Left Tibia CoM
RTICM	Right Tibia CoM
LFOCM	Left Foot CoM
RFOCM	Right Foot CoM
WBCOM	Whole Body CoM

HEDCM,WBCOM
THRCM,WBCOM
PELCM,WBCOM
LHUCM,WBCOM
LRACM,WBCOM
LHACM,WBCOM

RHUCM,WBCOM
RRACM,WBCOM
RHACM,WBCOM
LFECM,WBCOM
LTICM,WBCOM
LFOCM,WBCOM
RFECM,WBCOM
RTICM,WBCOM
RFOCM,WBCOM

[Joint Centers & CoM]

LSJC	Left Shoulder Joint Center
RSJC	Right Shoulder Joint Center
LEJC	Left Elbow Joint Center
REJC	Right Elbow Joint Center
LWJC	Left Wrist Joint Center
RWJC	Right Wrist Joint Center
LFIN	Left ForeFinger
RFIN	Right ForeFinger
LHJC	Left Hip Joint Center
RHJC	Right Hip Joint Center
LKJC	Left Knee Joint Center
RKJC	Right Knee Joint Center
LAJC	Left Ankle Joint Center
RAJC	Right Ankle Joint Center
LSID	L5S1 Intervertebral Disc
LTOE	Left Toe
RTOE	Right Toe

HEDCM	Head CoM
THRCM	Thorax CoM
PELCM	Pelvis CoM
LHUCM	Left Humerus CoM
RHUCM	Right Humerus CoM
LRACM	Left Radius CoM
RRACM	Right Radius CoM
LHACM	Left Hand CoM
RHACM	Right Hand CoM
LFECM	Left Femur CoM
RFECM	Right Femur CoM
LTICM	Left Tibia CoM
RTICM	Right Tibia CoM
LFOCM	Left Foot CoM

Appendix J. (Continued)

RFOCM	Right Foot CoM
WBCOM	Whole Body CoM

LSJC,LEJC
LEJC,LWJC
LWJC,LFIN
RSJC,REJC
REJC,RWJC
RWJC,RFIN
LSJC,RSJC
LSJC,LSID
RSJC,LSID
LSID,LHJC
LSID,RHJC
LHJC,RHJC
LHJC,LKJC
LKJC,LAJC
LAJC,LTOE
RHJC,RKJC
RKJC,RAJC
RAJC,RTOE

[Kinematics1-Joint Angles]

Neck_Angle	Neck Angle
Spine_Angle	Lumbar Spine Angle
LClavicle_Angle	Left Clavicle Angle
RClavicle_Angle	Right Clavicle Angle
LScapula_Angle	Left Scapula Angle
RScapula_Angle	Right Scapula Angle
LShoulder_Angle	Left Shoulder Angle
RShoulder_Angle	Right Shoulder Angle
LElbow_Angle	Left Elbow Angle
RElbow_Angle	Right Elbow Angle
LWrist_Angle	Left Wrist Angle
RWrist_Angle	Right Wrist Angle
LHip_Angle	Left Hip Angle
RHip_Angle	Right Hip Angle
LKnee_Angle	Left Knee Angle
RKnee_Angle	Right Knee Angle
LAnkle_Angle	Left Ankle Angle
RAnkle_Angle	Right Ankle Angle

[Kinematics2-Linear Velocity]

Head_LinVel	Linear Velocity Head CoM
Thorax_LinVel	Linear Velocity Thorax CoM
Pelvis_LinVel	Linear Velocity Pelvis CoM
LHumerus_LinVel	Linear Velocity Left Humerus CoM
RHumerus_LinVel	Linear Velocity Right Humerus CoM
LRadius_LinVel	Linear Velocity Left Radius CoM
RRadius_LinVel	Linear Velocity Right Radius CoM
LHand_LinVel	Linear Velocity Left Hand CoM
RHand_LinVel	Linear Velocity Right Hand CoM
LFemur_LinVel	Linear Velocity Left Femur CoM
RFemur_LinVel	Linear Velocity Right Femur CoM
LTibia_LinVel	Linear Velocity Left Tibia CoM
RTibia_LinVel	Linear Velocity Right Tibia CoM
LFoot_LinVel	Linear Velocity Left Foot CoM
RFoot_LinVel	Linear Velocity Right Foot CoM

[Kinematics3-Absolute Linear Velocity]

Head_AbsLinVel	Absolute Linear Velocity Head CoM
Thorax_AbsLinVel	Absolute Linear Velocity Thorax CoM
Pelvis_AbsLinVel	Absolute Linear Velocity Pelvis CoM
LHumerus_AbsLinVel	Absolute Linear Velocity Left Humerus CoM
RHumerus_AbsLinVel	Absolute Linear Velocity Right Humerus CoM
LRadius_AbsLinVel	Absolute Linear Velocity Left Radius CoM
RRadius_AbsLinVel	Absolute Linear Velocity Right Radius CoM
LHand_AbsLinVel	Absolute Linear Velocity Left Hand CoM
RHand_AbsLinVel	Absolute Linear Velocity Right Hand CoM
LFemur_AbsLinVel	Absolute Linear Velocity Left Femur CoM
RFemur_AbsLinVel	Absolute Linear Velocity Right Femur CoM
LTibia_AbsLinVel	Absolute Linear Velocity Left Tibia CoM
RTibia_AbsLinVel	Absolute Linear Velocity Right Tibia CoM
LFoot_AbsLinVel	Absolute Linear Velocity Left Foot CoM
RFoot_AbsLinVel	Absolute Linear Velocity Right Foot CoM

[Kinematics4-Linear Acceleration]

Head_LinAcc	Linear Acceleration Head CoM
Thorax_LinAcc	Linear Acceleration Thorax CoM
Pelvis_LinAcc	Linear Acceleration Pelvis CoM
LHumerus_LinAcc	Linear Acceleration Left Humerus CoM
RHumerus_LinAcc	Linear Acceleration Right Humerus CoM
LRadius_LinAcc	Linear Acceleration Left Radius CoM
RRadius_LinAcc	Linear Acceleration Right Radius CoM
LHand_LinAcc	Linear Acceleration Left Hand CoM

Appendix J. (Continued)

RHand_LinAcc	Linear Acceleration Right Hand CoM
LFemur_LinAcc	Linear Acceleration Left Femur CoM
RFemur_LinAcc	Linear Acceleration Right Femur CoM
LTibia_LinAcc	Linear Acceleration Left Tibia CoM
RTibia_LinAcc	Linear Acceleration Right Tibia CoM
LFoot_LinAcc	Linear Acceleration Left Foot CoM
RFoot_LinAcc	Linear Acceleration Right Foot CoM

[Kinematics5-Absolute Linear Acceleration]

Head_AbsLinAcc	Absolute Linear Acceleration Head CoM
Thorax_AbsLinAcc	Absolute Linear Acceleration Thorax CoM
Pelvis_AbsLinAcc	Absolute Linear Acceleration Pelvis CoM
LHumerus_AbsLinAcc	Absolute Linear Acceleration Left Humerus CoM
RHumerus_AbsLinAcc	Absolute Linear Acceleration Right Humerus CoM
LRadius_AbsLinAcc	Absolute Linear Acceleration Left Radius CoM
RRadius_AbsLinAcc	Absolute Linear Acceleration Right Radius CoM
LHand_AbsLinAcc	Absolute Linear Acceleration Left Hand CoM
RHand_AbsLinAcc	Absolute Linear Acceleration Right Hand CoM
LFemur_AbsLinAcc	Absolute Linear Acceleration Left Femur CoM
RFemur_AbsLinAcc	Absolute Linear Acceleration Right Femur CoM
LTibia_AbsLinAcc	Absolute Linear Acceleration Left Tibia CoM
RTibia_AbsLinAcc	Absolute Linear Acceleration Right Tibia CoM
LFoot_AbsLinAcc	Absolute Linear Acceleration Left Foot CoM
RFoot_AbsLinAcc	Absolute Linear Acceleration Right Foot CoM

[Kinematics6-Angular Velocity (radians/s)]

Neck_AngVel	Angular Velocity Cervical Spine Joint (radians/s)
LSpine_AngVel	Angular Velocity Lumbar-Sacral Joint (radians/s)
LClav_AngVel	Angular Velocity LClavicle-Thoracic Joint (radians/s)
RClav_AngVel	Angular Velocity RClavicle-Thoracic Joint (radians/s)
LScap_AngVel	Angular Velocity LScapular-Thoracic Joint (radians/s)
RScap_AngVel	Angular Velocity RScapular-Thoracic Joint (radians/s)
LShoulder_AngVel	Angular Velocity Left Shoulder Joint Center (radians/s)
RShoulder_AngVel	Angular Velocity Right Shoulder Joint Center (radians/s)
LElbow_AngVel	Angular Velocity Left Elbow Joint Center (radians/s)
RElbow_AngVel	Angular Velocity Right Elbow Joint Center (radians/s)
LWrist_AngVel	Angular Velocity Left Wrist Joint Center (radians/s)
RWrist_AngVel	Angular Velocity Right Wrist Joint Center (radians/s)
LHip_AngVel	Angular Velocity Left Hip Joint Center (radians/s)
RHip_AngVel	Angular Velocity Right Hip Joint Center (radians/s)
LKnee_AngVel	Angular Velocity Left Knee Joint Center (radians/s)
RKnee_AngVel	Angular Velocity Right Knee Joint Center (radians/s)

LAnkle_AngVel	Angular Velocity Left Ankle Joint Center (radians/s)
RAnkle_AngVel	Angular Velocity Right Ankle Joint Center (radians/s)

[Kinematics7-Angular Velocity (degrees/s)]

Neck_AngVelDeg	Angular Velocity Cervical Spine Joint (degrees/s)
LSpine_AngVelDeg	Angular Velocity Lumbar-Sacral Joint (degrees/s)
LClav_AngVelDeg	Angular Velocity LClavicle-Thoracic Joint (degrees/s)
RClav_AngVelDeg	Angular Velocity RClavicle-Thoracic Joint (degrees/s)
LScap_AngVelDeg	Angular Velocity LScapular-Thoracic Joint (degrees/s)
RScap_AngVelDeg	Angular Velocity RScapular-Thoracic Joint (degrees/s)
LShoulder_AngVelDeg	Angular Velocity Left Shoulder Joint Center (degrees/s)
RShoulder_AngVelDeg	Angular Velocity Right Shoulder Joint Center (degrees/s)
LElbow_AngVelDeg	Angular Velocity Left Elbow Joint Center (degrees/s)
RElbow_AngVelDeg	Angular Velocity Right Elbow Joint Center (degrees/s)
LWrist_AngVelDeg	Angular Velocity Left Wrist Joint Center (degrees/s)
RWrist_AngVelDeg	Angular Velocity Right Wrist Joint Center (degrees/s)
LHip_AngVelDeg	Angular Velocity Left Hip Joint Center (degrees/s)
RHip_AngVelDeg	Angular Velocity Right Hip Joint Center (degrees/s)
LKnee_AngVelDeg	Angular Velocity Left Knee Joint Center (degrees/s)
RKnee_AngVelDeg	Angular Velocity Right Knee Joint Center (degrees/s)
LAnkle_AngVelDeg	Angular Velocity Left Ankle Joint Center (degrees/s)
RAnkle_AngVelDeg	Angular Velocity Right Ankle Joint Center (degrees/s)

[Kinematics8-Angular Acceleration (radians/s2)]

Neck_AngAcc	Angular Accleration Cervical Spine Joint (radians/s2)
LSpine_AngAcc	Angular Accleration Lumbar-Sacral Joint (radians/s2)
LClav_AngAcc	Angular Accleration LClavicle-Thoracic Joint (radians/s2)
RClav_AngAcc	Angular Accleration RClavicle-Thoracic Joint (radians/s2)
LScap_AngAcc	Angular Accleration LScapular-Thoracic Joint (radians/s2)
RScap_AngAcc	Angular Accleration RScapular-Thoracic Joint (radians/s2)
LShoulder_AngAcc	Angular Accleration Left Shoulder Joint Center (radians/s2)
RShoulder_AngAcc	Angular Accleration Right Shoulder Joint Center (radians/s2)
LElbow_AngAcc	Angular Accleration Left Elbow Joint Center (radians/s2)
RElbow_AngAcc	Angular Accleration Right Elbow Joint Center (radians/s2)
LWrist_AngAcc	Angular Accleration Left Wrist Joint Center (radians/s2)
RWrist_AngAcc	Angular Accleration Right Wrist Joint Center (radians/s2)
LHip_AngAcc	Angular Accleration Left Hip Joint Center (radians/s2)
RHip_AngAcc	Angular Accleration Right Hip Joint Center (radians/s2)
LKnee_AngAcc	Angular Accleration Left Knee Joint Center (radians/s2)
RKnee_AngAcc	Angular Accleration Right Knee Joint Center (radians/s2)
LAnkle_AngAcc	Angular Accleration Left Ankle Joint Center (radians/s2)

RAnkle_AngAcc	Angular Accleration Right Ankle Joint Center (radians/s2)

[Kinematics9-Angular Acceleration (degrees/s2)]

Neck_AngAccDeg	Angular Accleration Cervical Spine Joint (degrees/s2)
LSpine_AngAccDeg	Angular Accleration Lumbar-Sacral Joint (degrees/s2)
LClav_AngAccDeg	Angular Accleration LClavicle-Thoracic Joint (degrees/s2)
RClav_AngAccDeg	Angular Accleration RClavicle-Thoracic Joint (degrees/s2)
LScap_AngAccDeg	Angular Accleration LScapular-Thoracic Joint (degrees/s2)
RScap_AngAccDeg	Angular Accleration RScapular-Thoracic Joint (degrees/s2)
LShoulder_AngAccDeg	Angular Accleration Left Shoulder Joint Center (degrees/s2)
RShoulder_AngAccDeg	Angular Accleration Right Shoulder Joint Center (degrees/s2)
LElbow_AngAccDeg	Angular Accleration Left Elbow Joint Center (degrees/s2)
RElbow_AngAccDeg	Angular Accleration Right Elbow Joint Center (degrees/s2)
LWrist_AngAccDeg	Angular Accleration Left Wrist Joint Center (degrees/s2)
RWrist_AngAccDeg	Angular Accleration Right Wrist Joint Center (degrees/s2)
LHip_AngAccDeg	Angular Accleration Left Hip Joint Center (degrees/s2)
RHip_AngAccDeg	Angular Accleration Right Hip Joint Center (degrees/s2)
LKnee_AngAccDeg	Angular Accleration Left Knee Joint Center (degrees/s2)
RKnee_AngAccDeg	Angular Accleration Right Knee Joint Center (degrees/s2)
LAnkle_AngAccDeg	Angular Accleration Left Ankle Joint Center (degrees/s2)
RAnkle_AngAccDeg	Angular Accleration Right Ankle Joint Center (degrees/s2)

[Kinetics1-Forces]

LWrist_Force	Internal Forces acting at Left Wrist Joint Center
RWrist_Force	Internal Forces acting at Right Wrist Joint Center
LElbow_Force	Internal Forces acting at Left Elbow Joint Center
RElbow_Force	Internal Forces acting at Right Elbow Joint Center
LShoulder_Force	Internal Forces acting at Left Shoulder Joint Center
RShoulder_Force	Internal Forces acting at Right Shoulder Joint Center
Spine_Force	Internal Forces acting at Lumbar-Sacral Intervertebral Disc
LHip_Force	Internal Forces acting at Left Hip Joint Center
RHip_Force	Internal Forces acting at Right Hip Joint Center
LKnee_Force	Internal Forces acting at Left Knee Joint Center
RKnee_Force	Internal Forces acting at Right Knee Joint Center
LAnkle_Force	Internal Forces acting at Left Ankle Joint Center
RAnkle_Force	Internal Forces acting at Right Ankle Joint Center

Appendix J. (Continued)

[Kinetics2-Moments]

LWrist_Moment	Internal Moment acting at Left Wrist Joint Center
RWrist_Moment	Internal Moment acting at Right Wrist Joint Center
LElbow_Moment	Internal Moment acting at Left Elbow Joint Center
RElbow_Moment	Internal Moment acting at Right Elbow Joint Center
LShoulder_Moment	Internal Moment acting at Left Shoulder Joint Center
RShoulder_Moment	Internal Moment acting at Right Shoulder Joint Center
Spine_Moment	Internal Moment acting at the Lumbar-Sacral Intervertebral Disc
LHip_Moment	Internal Moment acting at Left Hip Joint Center
RHip_Moment	Internal Moment acting at Right Hip Joint Center
LKnee_Moment	Internal Moment acting at Left Knee Joint Center
RKnee_Moment	Internal Moment acting at Right Knee Joint Center
LAnkle_Moment	Internal Moment acting at Left Ankle Joint Center
RAnkle_Moment	Internal Moment acting at Right Ankle Joint Center

[Kinetics3-Powers]

LWrist_Power	Power acting at Left Wrist Joint Center
RWrist_Power	Power acting at Right Wrist Joint Center
LElbow_Power	Power acting at Left Elbow Joint Center
RElbow_Power	Power acting at Right Elbow Joint Center
LShoulder_Power	Power acting at Left Shoulder Joint Center
RShoulder_Power	Power acting at Right Shoulder Joint Center
Spine_Power	Power acting at the Lumbar-Sacral Intervertebral Disc
LHip_Power	Power acting at Left Hip Joint Center
RHip_Power	Power acting at Right Hip Joint Center
LKnee_Power	Power acting at Left Knee Joint Center
RKnee_Power	Power acting at Right Knee Joint Center
LAnkle_Power	Power acting at Left Ankle Joint Center
RAnkle_Power	Power acting at Right Ankle Joint Center

[Bones]
HEADbone_O
HEADbone_P
HEADbone_A
HEADbone_L

CSPINEbone_O
CSPINEbone_P
CSPINEbone_A
CSPINEbone_L

Appendix J. (Continued)

THORAXbone_O
THORAXbone_P
THORAXbone_A
THORAXbone_L

PELVISbone_O
PELVISbone_P
PELVISbone_A
PELVISbone_L

SACRUMbone_O
SACRUMbone_P
SACRUMbone_A
SACRUMbone_L

LCLAVbone_O
LCLAVbone_P
LCLAVbone_A
LCLAVbone_L
RCLAVbone_O
RCLAVbone_P
RCLAVbone_A
RCLAVbone_L

LHUMbone_O
LHUMbone_P
LHUMbone_A
LHUMbone_L
RHUMbone_O
RHUMbone_P
RHUMbone_A
RHUMbone_L

LRADbone_O
LRADbone_P
LRADbone_A
LRADbone_L
RRADbone_O
RRADbone_P
RRADbone_A
RRADbone_L

LHANDbone_O
LHANDbone_P

LHANDbone_A
LHANDbone_L
RHANDbone_O
RHANDbone_P
RHANDbone_A
RHANDbone_L

LFEMURbone_O
LFEMURbone_P
LFEMURbone_A
LFEMURbone_L
RFEMURbone_O
RFEMURbone_P
RFEMURbone_A
RFEMURbone_L

LTIBIAbone_O
LTIBIAbone_P
LTIBIAbone_A
LTIBIAbone_L
RTIBIAbone_O
RTIBIAbone_P
RTIBIAbone_A
RTIBIAbone_L

LFOOTbone_O
LFOOTbone_P
LFOOTbone_A
LFOOTbone_L
RFOOTbone_O
RFOOTbone_P
RFOOTbone_A
RFOOTbone_L

Head = HEADbone_O,HEADbone_P,HEADbone_A,HEADbone_L
CSpine = CSPINEbone_O,CSPINEbone_P,CSPINEbone_A,CSPINEbone_L
Thorax = THORAXbone_O,THORAXbone_P,THORAXbone_A, THORAXbone_L
Pelvis = PELVISbone_O,PELVISbone_P,PELVISbone_A,PELVISbone_L
Sacrum = SACRUMbone_O,SACRUMbone_P,SACRUMbone_A, SACRUMbone_L

LeftClavicle = LCLAVbone_O,LCLAVbone_P,LCLAVbone_A,LCLAVbone_L

Appendix J. (Continued)

```
RightClavicle = RCLAVbone_O,RCLAVbone_P,RCLAVbone_A,RCLAVbone_L
LeftHumerus = LHUMbone_O,LHUMbone_P,LHUMbone_A,LHUMbone_L
RightHumerus        =
RHUMbone_O,RHUMbone_P,RHUMbone_A,RHUMbone_L
LeftRadius    = LRADbone_O,LRADbone_P,LRADbone_A,LRADbone_L
RightRadius   = RRADbone_O,RRADbone_P,RRADbone_A,RRADbone_L
LeftHand      = LHANDbone_O,LHANDbone_P,LHANDbone_A,LHANDbone_L
RightHand     = RHANDbone_O,RHANDbone_P,RHANDbone_A,RHANDbone_L

LeftFemur     = LFEMURbone_O,LFEMURbone_P,LFEMURbone_A,
LFEMURbone_L
RightFemur    = RFEMURbone_O,RFEMURbone_P,RFEMURbone_A,
RFEMURbone_L
LeftTibia     = LTIBIAbone_O,LTIBIAbone_P,LTIBIAbone_A,LTIBIAbone_L
RightTibia    = RTIBIAbone_O,RTIBIAbone_P,RTIBIAbone_A,RTIBIAbone_L
LeftFoot      = LFOOTbone_O,LFOOTbone_P,LFOOTbone_A,LFOOTbone_L
RightFoot     = RFOOTbone_O,RFOOTbone_P,RFOOTbone_A,RFOOTbone_L


[Left Muscle Attachments]
LMastoidProcess
LOcciput

LPostT1
LPostT7
LMidSternum
LAntT12

LLatClavicle
LMedClavicle
LSupraGlenoidTubercle

LUppAntHumerus
LUppPostHumerus
LLowAntHumerus
LLowLatHumerus
LMedHumeralEpicondyle
LLatHumeralEpicondyle
LUlnarOlecranon
LUlnarTuberosity
LRadialTuberosity
LUppMedUlna
LMidLatRadius
LLowLatRadius
```

LFlexorRetinaculum
LExtensorRetinaculum
LPal2MetaCarpal
LPal5MetaCarpal
LPal3DistalPhalanx
LDor3DistalPhalanx

LIliacCrest
LIliacFossa
LAntInfIliacSpine
LPelvicBrim
LPostSacrum
LIschialTuberosity

LGreaterTrochanter
LLesserTrochanter
LUppFemoralShaft
LMidFemoralShaft
LLatFemoralCondyle
LMedFemoralCondyle
LPatella
LMedTibialCondyle
LHeadFibula
LTibialTubercle
LUppLatTibia
LMidFibula
LInfExtensorRetinaculum
LCalcaneous
LMedCuneiform

LOcciput,LLatClavicle
LMastoidProcess,LPostT1
LMastoidProcess,LMedClavicle

LSupraGlenoidTubercle,LRadialTuberosity
LLowAntHumerus,LUlnarTuberosity
LLowLatHumerus,LLowLatRadius
LUppPostHumerus,LUlnarOlecranon
LMedHumeralEpicondyle,LMidLatRadius
LUppMedUlna,LMidLatRadius
LMedHumeralEpicondyle,LPal5MetaCarpal
LMedHumeralEpicondyle,LPal2MetaCarpal
LUppMedUlna,LFlexorRetinaculum
LFlexorRetinaculum,LPal3DistalPhalanx

LLatHumeralEpicondyle,LExtensorRetinaculum
LExtensorRetinaculum,LDor3DistalPhalanx

LPostT1,LLatClavicle
LPostT7,LLatClavicle
LMidSternum,LUppAntHumerus
LPostT7,LUppPostHumerus
LPostSacrum,LUppPostHumerus

LAntT12,LPelvicBrim
LIliacFossa,LPelvicBrim
LPelvicBrim,LLesserTrochanter
LIliacCrest,LGreaterTrochanter
LAntInfIliacSpine,LPatella
LIschialTuberosity,LMedTibialCondyle
LIschialTuberosity,LHeadFibula
LIschialTuberosity,LMidFemoralShaft
LIschialTuberosity,LMedFemoralCondyle

LUppFemoralShaft,LPatella
LPatella,LTibialTubercle
LLatFemoralCondyle,LCalcaneous
LMedFemoralCondyle,LCalcaneous
LUppLatTibia,LInfExtensorRetinaculum
LInfExtensorRetinaculum,LMedCuneiform
LMidFibula,LInfExtensorRetinaculum

[Right Muscle Attachments]
RMastoidProcess
ROcciput

RPostT1
RPostT7
RMidSternum
RAntT12

RLatClavicle
RMedClavicle
RSupraGlenoidTubercle

RUppAntHumerus
RUppPostHumerus
RLowAntHumerus

Appendix J. (Continued)

RLowLatHumerus
RMedHumeralEpicondyle
RLatHumeralEpicondyle
RUlnarOlecranon
RUlnarTuberosity
RRadialTuberosity
RUppMedUlna
RMidLatRadius
RLowLatRadius
RFlexorRetinaculum
RExtensorRetinaculum
RPal2MetaCarpal
RPal5MetaCarpal
RPal3DistalPhalanx
RDor3DistalPhalanx

RIliacCrest
RIliacFossa
RAntInfIliacSpine
RPelvicBrim
RPostSacrum
RIschialTuberosity

RGreaterTrochanter
RLesserTrochanter
RUppFemoralShaft
RMidFemoralShaft
RLatFemoralCondyle
RMedFemoralCondyle
RPatella
RMedTibialCondyle
RHeadFibula
RTibialTubercle
RUppLatTibia
RMidFibula
RInfExtensorRetinaculum
RCalcaneous
RMedCuneiform

ROcciput,RLatClavicle
RMastoidProcess,RPostT1
RMastoidProcess,RMedClavicle

RSupraGlenoidTubercle,RRadialTuberosity

RLowAntHumerus,RUlnarTuberosity
RLowLatHumerus,RLowLatRadius
RUppPostHumerus,RUlnarOlecranon
RMedHumeralEpicondyle,RMidLatRadius
RUppMedUlna,RMidLatRadius
RMedHumeralEpicondyle,RPal5MetaCarpal
RMedHumeralEpicondyle,RPal2MetaCarpal
RUppMedUlna,RFlexorRetinaculum
RFlexorRetinaculum,RPal3DistalPhalanx
RLatHumeralEpicondyle,RExtensorRetinaculum
RExtensorRetinaculum,RDor3DistalPhalanx

RPostT1,RLatClavicle
RPostT7,RLatClavicle
RMidSternum,RUppAntHumerus
RPostT7,RUppPostHumerus
RPostSacrum,RUppPostHumerus

RAntT12,RPelvicBrim
RIliacFossa,RPelvicBrim
RPelvicBrim,RLesserTrochanter
RIliacCrest,RGreaterTrochanter
RAntInfIliacSpine,RPatella
RIschialTuberosity,RMedTibialCondyle
RIschialTuberosity,RHeadFibula
RIschialTuberosity,RMidFemoralShaft
RIschialTuberosity,RMedFemoralCondyle

RUppFemoralShaft,RPatella
RPatella,RTibialTubercle
RLatFemoralCondyle,RCalcaneous
RMedFemoralCondyle,RCalcaneous
RUppLatTibia,RInfExtensorRetinaculum
RInfExtensorRetinaculum,RMedCuneiform
RMidFibula,RInfExtensorRetinaculum

[Left Muscle Lengths]

LUppTrapeziusLength	Length of Left Upper Trapezius
LUppSpleniusCapitisLength	Length of Left Upper Splenius Capitis
LSternoMastoidLength	Length of Left SternoMastoid
LBicepsBrachiiLength	Length of Left Biceps Brachii
LBrachialisLength	Length of Left Brachialis

Appendix J. (Continued)

LBrachioradialisLength	Length of Left Brachioradialis
LTricepsBrachiiLength	Length of Left Triceps Brachii
LLongHeadPronatorTeresLength	Length of Left Long Head Pronator Teres
LShortHeadPronatorTeresLength	Length of Left Short Head Pronator Teres
LFlexorCarpiUlnarisLength	Length of Left Flexor Carpi Ulnaris
LFlexorCarpiRadialisLength	Length of Left Flexor Carpi Radialis
LFlexorDigitorumLength	Length of Left Flexor Digitorum
LExtensorDigitorumLength	Length of Left Extensor Digitorum

LMidTrapeziusLength	Length of Left Mid Section of Trapezius
LLowTrapeziusLength	Length of Left Lower Section of Trapezius
LPectoralisMajorLength	Length of Left Pectoralis Major
LUppLatissimusDorsiLength	Length of Left Upper Section of Latissimus Dorsi
LLowLatissimusDorsiLength	Length of Left Lower Section of Latissimus Dorsi

LPsoasLength	Length of Left Psoas
LIliacusLength	Length of Left Iliacus
LGluteusMediusLength	Length of Left Gluteus Medius
LRectusFemorisLength	Length of Left Rectus Femoris
LSemimembranosusLength	Length of Left Semimembranosus
LBicepsFemorisLength	Length of Left Biceps Femoris
LAdductorMagnusLength	Length of Left Adductor Magnus
LGracilisLength	Length of Left Gracilis

LVastiLength	Length of Left Vasti
LLatHeadGastrocnemiusLength	Length of Left Lateral Head of Gastrocnemius
LMedHeadGastrocnemiusLength	Length of Left Medial Head of Gastrocnemius
LTibialisAntLength	Length of Left Tibialis Anterior
LExtensorHallucisLongusLength	Length of Left Extensor Hallucis Longus

[Right Muscle Lengths]

RUppTrapeziusLength	Length of Right Upper Trapezius
RUppSpleniusCapitisLength	Length of Right Upper Splenius Capitis
RSternoMastoidLength	Length of Right SternoMastoid

RBicepsBrachiiLength	Length of Right Biceps Brachii
RBrachialisLength	Length of Right Brachialis
RBrachioradialisLength	Length of Right Brachioradialis
RTricepsBrachiiLength	Length of Right Triceps Brachii
RLongHeadPronatorTeresLength	Length of Right Long Head Pronator Teres
RShortHeadPronatorTeresLength	Length of Right Short Head Pronator Teres

Appendix J. (Continued)

RFlexorCarpiUlnarisLength	Length of Right Flexor Carpi Ulnaris
RFlexorCarpiRadialisLength	Length of Right Flexor Carpi Radialis
RFlexorDigitorumLength	Length of Right Flexor Digitorum
RExtensorDigitorumLength	Length of Right Extensor Digitorum
RMidTrapeziusLength	Length of Right Mid Section of Trapezius
RLowTrapeziusLength	Length of Right Lower Section of Trapezius
RPectoralisMajorLength	Length of Right Pectoralis Major
RUppLatissimusDorsiLength	Length of Right Upper Section of Latissimus Dorsi
RLowLatissimusDorsiLength	Length of Right Lower Section of Latissimus Dorsi
RPsoasLength	Length of Right Psoas
RIliacusLength	Length of Right Iliacus
RGluteusMediusLength	Length of Right Gluteus Medius
RRectusFemorisLength	Length of Right Rectus Femoris
RSemimembranosusLength	Length of Right Semimembranosus
RBicepsFemorisLength	Length of Right Biceps Femoris
RAdductorMagnusLength	Length of Right Adductor Magnus
RGracilisLength	Length of Right Gracilis
RVastiLength	Length of Right Vasti
RLatHeadGastrocnemiusLength	Length of Right Lateral Head of Gastrocnemius
RMedHeadGastrocnemiusLength	Length of Right Medial Head of Gastrocnemius
RTibialisAntLength	Length of Right Tibialis Anterior
RExtensorHallucisLongusLength	Length of Right Extensor Hallucis Longus

[Output Data]
LShoulder_Angle
RShoulder_Angle
LElbow_Angle
RElbow_Angle
LWrist_Angle
RWrist_Angle

LShoulder_Force
RShoulder_Force
LElbow_Force
RElbow_Force
LWrist_Force
RWrist_Force

LShoulder_Moment

Appendix J. (Continued)

RShoulder_Moment
LElbow_Moment
RElbow_Moment
LWrist_Moment
RWrist_Moment

LShoulder_Power
RShoulder_Power
LElbow_Power
RElbow_Power
LWrist_Power
RWrist_Power

```
{*
=============================================================
=========== *}
                 Whole-body biomechanical model for
         3D dynamic kinematic and kinetic analysis of human motion
                                2005
                        John D Lloyd, Ph.D.
             VA Patient Safety Research Center, Tampa, Florida
{*
=============================================================
=========== *}

{*
=============================================================
=========== *}
         PART 1 - REPLACE STATIC AND OCCLUDED MARKERS
{*
=============================================================
=========== *}


{* ====================================== *}
{* MACROS                                 *}
{* ====================================== *}

macro REPLACE4(p1,p2,p3,p4)
{*Replaces any point missing from set of four fixed in a segment *}
s234=[p3,p2-p3,p3-p4]
p1V=Average(p1/s234)*s234
s341=[p4,p3-p4,p4-p1]
p2V=Average(p2/s341)*s341
s412=[p1,p4-p1,p1-p2]
p3V=Average(p3/s412)*s412
s123=[p2,p1-p2,p2-p3]
p4V=Average(p4/s123)*s123
p1= p1 ? p1V
p2= p2 ? p2V
p3= p3 ? p3V
p4= p4 ? p4V
OUTPUT(p1,p2,p3,p4)
endmacro

{* ====================================== *}
```

```
macro REPLACE5(p1,p2,p3,p4,p5)
{*Replaces any point missing from set of five fixed in a segment*}

{*SECTION FOR INITIALISATION OF VIRTUAL POINTS*}
{*REPLACE4*}
s123=[p2,p1-p2,p2-p3]
p4V1=Average(p4/s123)*s123
s124=[p2,p1-p2,p2-p4]
p3V1=Average(p3/s124)*s124
s134=[p3,p1-p3,p3-p4]
p2V1=Average(p2/s134)*s134
s234=[p3,p2-p3,p3-p4]
p1V1=Average(p1/s234)*s234

{*Addition required for REPLACE5*}
s123=[p2,p1-p2,p2-p3]
p5V1=Average(p5/s123)*s123
s124=[p2,p1-p2,p2-p4]
p5V2=Average(p5/s124)*s124
s125=[p2,p1-p2,p2-p5]
p3V2=Average(p3/s125)*s125
p4V2=Average(p4/s125)*s125
s134=[p3,p1-p3,p3-p4]
p5V3=Average(p5/s134)*s134
s135=[p3,p1-p3,p3-p5]
p2V2=Average(p2/s135)*s135
p4V3=Average(p4/s135)*s135
s145=[p4,p1-p4,p4-p5]
p2V3=Average(p2/s145)*s145
p3V3=Average(p3/s145)*s145
s234=[p3,p2-p3,p3-p4]
p5V4=Average(p5/s234)*s234
s235=[p3,p2-p3,p3-p5]
p1V2=Average(p1/s235)*s235
p4V4=Average(p4/s235)*s235
s245=[p4,p2-p4,p4-p5]
p1V3=Average(p1/s245)*s245
p3V4=Average(p3/s245)*s245
s345=[p4,p3-p4,p4-p5]
p1V4=Average(p1/s345)*s345
p2V4=Average(p2/s345)*s345
```

```
{*SECTION FOR SPECIFICATION OF VIRTUAL POINTS*}
p1= p1 ? p1V1 ? p1V2 ? p1V3 ? p1V4
p2= p2 ? p2V1 ? p2V2 ? p2V3 ? p2V4
p3= p3 ? p3V1 ? p3V2 ? p3V3 ? p3V4
p3= p3 ? p3V1 ? p3V2 ? p3V3 ? p3V4
p4= p4 ? p4V1 ? p4V2 ? p4V3 ? p4V4
p5= p5 ? p5V1 ? p5V2 ? p5V3 ? p5V4
OUTPUT(p1,p2,p3,p4,p5)
endmacro

{* ==================================== *}

macro REPLACE6(p1,p2,p3,p4,p5,p6)
{*Replaces any point missing from set of six fixed in a segment*}

{*SECTION FOR INITIALISATION OF VIRTUAL POINTS*}
{*REPLACE4*}
s123=[p2,p1-p2,p2-p3]
p4V1=Average(p4/s123)*s123
s124=[p2,p1-p2,p2-p4]
p3V1=Average(p3/s124)*s124
s134=[p3,p1-p3,p3-p4]
p2V1=Average(p2/s134)*s134
s234=[p3,p2-p3,p3-p4]
p1V1=Average(p1/s234)*s234

{*Addition required for REPLACE5*}
s123=[p2,p1-p2,p2-p3]
p5V1=Average(p5/s123)*s123
s124=[p2,p1-p2,p2-p4]
p5V2=Average(p5/s124)*s124
s125=[p2,p1-p2,p2-p5]
p3V2=Average(p3/s125)*s125
p4V2=Average(p4/s125)*s125
s134=[p3,p1-p3,p3-p4]
p5V3=Average(p5/s134)*s134
s135=[p3,p1-p3,p3-p5]
p2V2=Average(p2/s135)*s135
p4V3=Average(p4/s135)*s135
s145=[p4,p1-p4,p4-p5]
p2V3=Average(p2/s145)*s145
p3V3=Average(p3/s145)*s145
s234=[p3,p2-p3,p3-p4]
```

```
p5V4=Average(p5/s234)*s234
s235=[p3,p2-p3,p3-p5]
p1V2=Average(p1/s235)*s235
p4V4=Average(p4/s235)*s235
s245=[p4,p2-p4,p4-p5]
p1V3=Average(p1/s245)*s245
p3V4=Average(p3/s245)*s245
s345=[p4,p3-p4,p4-p5]
p1V4=Average(p1/s345)*s345
p2V4=Average(p2/s345)*s345

{*Addition requiredfor REPLACE6*}
s123=[p2,p1-p2,p2-p3]
p6V1=Average(p6/s123)*s123
s124=[p2,p1-p2,p2-p4]
p6V2=Average(p6/s124)*s124
s125=[p2,p1-p2,p2-p5]
p6V3=Average(p6/s125)*s125
s126=[p2,p1-p2,p2-p6]
p3V5=Average(p3/s126)*s126
p4V5=Average(p4/s126)*s126
p5V5=Average(p5/s126)*s126
s134=[p3,p1-p3,p3-p4]
p6V4=Average(p6/s134)*s134
s135=[p3,p1-p3,p3-p5]
p6V5=Average(p6/s135)*s135
s136=[p3,p1-p3,p3-p6]
p2V5=Average(p2/s136)*s136
p4V6=Average(p4/s136)*s136
p5V6=Average(p5/s136)*s136
s145=[p4,p1-p4,p4-p5]
p6V6=Average(p6/s145)*s145
s146=[p4,p1-p4,p4-p6]
p2V6=Average(p2/s146)*s146
p3V6=Average(p3/s146)*s146
p5V7=Average(p5/s146)*s146
s156=[p5,p1-p5,p5-p6]
p2V7=Average(p2/s156)*s156
p3V7=Average(p3/s156)*s156
p4V7=Average(p4/s156)*s156
s234=[p3,p2-p3,p3-p4]
p6V7=Average(p6/s234)*s234
s235=[p3,p2-p3,p3-p5]
```

```
p6V8=Average(p6/s235)*s235
s236=[p3,p2-p3,p3-p6]
p1V5=Average(p1/s236)*s236
p4V8=Average(p4/s236)*s236
p5V8=Average(p5/s236)*s236
s245=[p4,p2-p4,p4-p5]
p6V9=Average(p6/s245)*s245
s246=[p4,p2-p4,p4-p6]
p1V6=Average(p1/s246)*s246
p3V8=Average(p3/s246)*s246
p5V9=Average(p5/s246)*s246
s256=[p5,p2-p5,p5-p6]
p1V7=Average(p1/s256)*s256
p3V9=Average(p3/s256)*s256
p4V9=Average(p4/s256)*s256
s345=[p4,p3-p4,p4-p5]
p6V10=Average(p6/s345)*s345
s346=[p4,p3-p4,p4-p6]
p1V8=Average(p1/s346)*s346
p2V8=Average(p2/s346)*s346
p5V10=Average(p5/s346)*s346
s356=[p5,p3-p5,p5-p6]
p1V9=Average(p1/s356)*s356
p2V9=Average(p2/s356)*s356
p4V10=Average(p4/s356)*s356
s456=[p5,p4-p5,p5-p6]
p1V10=Average(p1/s456)*s456
p2V10=Average(p2/s456)*s456
p3V10=Average(p3/s456)*s456

{*SECTION FOR SPECIFICATION OF VIRTUAL POINTS*}
p1= p1 ? p1V1 ? p1V2 ? p1V3 ? p1V4 ? p1V5 ? p1V6 ? p1V7 ? p1V8 ? p1V9 ?
p1V10
p2= p2 ? p2V1 ? p2V2 ? p2V3 ? p2V4 ? p2V5 ? p2V6 ? p2V7 ? p2V8 ? p2V9 ?
p2V10
p3= p3 ? p3V1 ? p3V2 ? p3V3 ? p3V4 ? p3V5 ? p3V6 ? p3V7 ? p3V8 ? p3V9 ?
p3V10
p3= p3 ? p3V1 ? p3V2 ? p3V3 ? p3V4 ? p3V5 ? p3V6 ? p3V7 ? p3V8 ? p3V9 ?
p3V10
p4= p4 ? p4V1 ? p4V2 ? p4V3 ? p4V4 ? p4V5 ? p4V6 ? p4V7 ? p4V8 ? p4V9 ?
p4V10
p5= p5 ? p5V1 ? p5V2 ? p5V3 ? p5V4 ? p5V5 ? p5V6 ? p5V7 ? p5V8 ? p5V9 ?
p5V10
```

```
p6= p6 ? p6V1 ? p6V2 ? p6V3 ? p6V4 ? p6V5 ? p6V6 ? p6V7 ? p6V8 ? p6V9 ?
p6V10
OUTPUT(p1,p2,p3,p4,p5,p6)
endmacro


{* ===================================== *}
{* OPTIONAL MARKERS                      *}
{* ===================================== *}

OptionalPoints(GLAB,LTEM,RTEM,LMAS,RMAS)
OptionalPoints(CSPN,CLAV,STRN,CHST)
OptionalPoints(LSCS,LSCI,RSCS,RSCI)
OptionalPoints(MPEL,LASI,RASI,LSIS,RSIS)
OptionalPoints(LACR,LHT1,LHT2,LHT3)
OptionalPoints(LELB,LMEL,LRT1,LRT2,LRT3)
OptionalPoints(LRAD,LULN,LFIN,LLFI)
OptionalPoints(RACR,RHT1,RHT2,RHT3)
OptionalPoints(RELB,RMEL,RRT1,RRT2,RRT3)
OptionalPoints(RRAD,RULN,RFIN,RLFI)
OptionalPoints(LFT1,LFT2,LFT3)
OptionalPoints(LKNE,LMKN,LTT1,LTT2,LTT3)
OptionalPoints(LANK,LMAN,LTOE,LLTO)
OptionalPoints(RFT1,RFT2,RFT3)
OptionalPoints(RKNE,RMKN,RTT1,RTT2,RTT3)
OptionalPoints(RANK,RMAN,RTOE,RLTO)


{* ===================================== *}
{* REPLACE OCCLUDED MARKERS 1            *}
{* ===================================== *}

{* Head *}
Replace5(GLAB,LTEM,RTEM,LMAS,RMAS)

{* Thorax *}
Replace6(CSPN,CLAV,STRN,CHST,LACR,RACR)

{* Pelvis *}
Replace5(MPEL,LASI,RASI,LSIS,RSIS)

{* Humeri *}
Replace5(LHT1,LHT2,LHT3,LELB,LMEL)
```

```
Replace5(RHT1,RHT2,RHT3,RELB,RMEL)

{* Radii *}
Replace6(LELB,LRT1,LRT2,LRT3,LRAD,LULN)
Replace6(RELB,RRT1,RRT2,RRT3,RRAD,RULN)

{* Hands *}
Replace4(LRAD,LULN,LFIN,LLFI)
Replace4(RRAD,RULN,RFIN,RLFI)

{* Femuri *}
Replace5(LFT1,LFT2,LFT3,LKNE,LMKN)
Replace5(RFT1,RFT2,RFT3,RKNE,RMKN)

{* Tibiae *}
Replace6(LKNE,LTT1,LTT2,LTT3,LANK,LMAN)
Replace6(RKNE,RTT1,RTT2,RTT3,RANK,RMAN)

{* Feet *}
Replace4(LANK,LMAN,LTOE,LLTO)
Replace4(RANK,RMAN,RTOE,RLTO)


{*
=============================================================
=========== *}
{* REPLACE STATIC MARKERS                                    *}
{*
==================================+==========================
=========== *}

{* Head Segment*}
PreHead=[GLAB,LTEM-RTEM,LTEM-GLAB]
If $Static==1 Then
$%LMAS=LMAS/PreHead
$%RMAS=RMAS/PreHead
PARAM($%LMAS,$%RMAS)
EndIf
LMASV=$%LMAS*PreHead
RMASV=$%RMAS*PreHead
RMAS=RMAS ? RMASV
LMAS=LMAS ? LMASV
OUTPUT(LMAS,RMAS)
```

```
{*Left Scapula Segment*}
PreLScapula=[LACR,LACR-CLAV,CLAV-STRN]
If $Static==1 Then
$%LSCS=LSCS/PreLScapula
$%LSCI=LSCI/PreLScapula
PARAM($%LSCS,$%LSCI)
EndIf
LSCSV=$%LSCS*PreLScapula
LSCIV=$%LSCI*PreLScapula
LSCS=LSCS ? LSCSV
LSCI=LSCI ? LSCIV
OUTPUT(LSCS,LSCI)

{*Right Scapula Segment*}
PreRScapula=[RACR,RACR-CLAV,CLAV-STRN]
If $Static==1 Then
$%RSCS=RSCS/PreRScapula
$%RSCI=RSCI/PreRScapula
PARAM($%RSCS,$%RSCI)
EndIf
RSCSV=$%RSCS*PreRScapula
RSCIV=$%RSCI*PreRScapula
RSCS=RSCS ? RSCSV
RSCI=RSCI ? RSCIV
OUTPUT(RSCS,RSCI)

{*Pelvis Segment1*}
PrePelvis1=[STRN,STRN-CLAV,CLAV-CSPN]
If $Static==1 Then
$%MPEL=MPEL/PrePelvis1
$%LASI=LASI/PrePelvis1
$%RASI=RASI/PrePelvis1
PARAM($%MPEL,$%LASI,$%RASI)
EndIf
MPELV=$%MPEL*PrePelvis1
LASIV=$%LASI*PrePelvis1
RASIV=$%RASI*PrePelvis1
MPEL=MPEL ? MPELV
LASI=LASI ? LASIV
RASI=RASI ? RASIV
OUTPUT(MPEL,LASI,RASI)
```

```
{*Pelvis Segment2*}
PrePelvis2=[MPEL,LASI-RASI,LASI-MPEL]
If $Static==1 Then
$%LSIS=LSIS/PrePelvis2
$%RSIS=RSIS/PrePelvis2
PARAM($%LSIS,$%RSIS)
EndIf
LSISV=$%LSIS*PrePelvis2
RSISV=$%RSIS*PrePelvis2
LSIS=LSIS ? LSISV
RSIS=RSIS ? RSISV
OUTPUT(LSIS,RSIS)


{* ==================================== *}
{* REPLACE OCCLUDED MARKERS 2            *}
{* ==================================== *}

{* Head *}
Replace5(GLAB,LTEM,RTEM,LMAS,RMAS)

{* Thorax *}
Replace6(CSPN,CLAV,STRN,CHST,LACR,RACR)

{* Pelvis *}
Replace5(MPEL,LASI,RASI,LSIS,RSIS)

{* Humeri *}
Replace5(LHT1,LHT2,LHT3,LELB,LMEL)
Replace5(RHT1,RHT2,RHT3,RELB,RMEL)

{* Radii *}
Replace6(LELB,LRT1,LRT2,LRT3,LRAD,LULN)
Replace6(RELB,RRT1,RRT2,RRT3,RRAD,RULN)

{* Hands *}
Replace4(LRAD,LULN,LFIN,LLFI)
Replace4(RRAD,RULN,RFIN,RLFI)

{* Femuri *}
Replace5(LFT1,LFT2,LFT3,LKNE,LMKN)
Replace5(RFT1,RFT2,RFT3,RKNE,RMKN)
```

```
{* Tibiae *}
Replace6(LKNE,LTT1,LTT2,LTT3,LANK,LMAN)
Replace6(RKNE,RTT1,RTT2,RTT3,RANK,RMAN)

{* Feet *}
Replace4(LANK,LMAN,LTOE,LLTO)
Replace4(RANK,RMAN,RTOE,RLTO)


{* ==================================== *}
{* END OF MODEL                        *}
{* ==================================== *}

{*============================================================
============ *}
                Whole-body biomechanical model for
      3D dynamic kinematic and kinetic analysis of human motion
                              2005
                        John D Lloyd, Ph.D.
            VA Patient Safety Research Center, Tampa, Florida
{*
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{*
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=========== *}
                PART 2 - BIOMECHANICAL MODELING
                              {*
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                        =========== *}


{* ============================ *}
{* MACROS                      *}
{* ============================ *}

macro AXISVISUALISATION(Segment)
ORIGIN#Segment=O(Segment)
AXISX#Segment={200,0,0}*Segment
AXISY#Segment={0,150,0}*Segment
AXISZ#Segment={0,0,100}*Segment
output(ORIGIN#Segment,AXISX#Segment,AXISY#Segment,AXISZ#Segment)
```

```
ENDMACRO

{* ========== *}

macro LINVELACC(Point,Name)
{* Calculates linear velocity in m/s and linear acceleration in m/s^2 of a point,
using numerical differentiation *}
{* Ref: Hildebrand, 1974; Kreyszig, 1983; Yakowitz, Sydney & Szidarovsky 1989
*}
$FrameTimeLength=1/$SamplingRate
Name#_LinVel=((Point[-2]-(8*Point[-1])+(8*Point[1])-
Point[2])/(12*$FrameTimeLength))/1000
Name#_LinAcc=((Name#_LinVel[-2]-(8*Name#_LinVel[-
1])+(8*Name#_LinVel[1])-Name#_LinVel[2])/(12*$FrameTimeLength))
Name#_AbsLinVel=sqrt((Name#_LinVel(1)*Name#_LinVel(1))+(Name#_LinVel(2
)*Name#_LinVel(2))+(Name#_LinVel(3)*Name#_LinVel(3)))
Name#_AbsLinAcc=sqrt((Name#_LinAcc(1)*Name#_LinAcc(1))+(Name#_LinAcc
(2)*Name#_LinAcc(2))+(Name#_LinAcc(3)*Name#_LinAcc(3)))
OUTPUT(Name#_LinVel,Name#_LinAcc,Name#_AbsLinVel,Name#_AbsLinAcc)
ENDMACRO

{* ========== *}

macro ANGVELACC(child,parent,Joint)
{* Calculates angular velocity in rad/s and angular acceleration in rad/s^2 at a
joint, using numerical differentiation *}
$FrameTimeLength=1/$SamplingRate
pi=3.1415927
Joint#Angle=<child,parent,xyz>
Joint={Joint#Angle(1),Joint#Angle(2),Joint#Angle(3)}
Rad#Joint=Joint*pi/180
Joint#_AngVel=((Rad#Joint[-2]-(8*Rad#Joint[-1])+(8*Rad#Joint[1])-
Rad#Joint[2])/(12*$FrameTimeLength))
Joint#_AngAcc=((Joint#_AngVel[-2]-(8*Joint#_AngVel[-1])+(8*Joint#_AngVel[1])-
Joint#_AngVel[2])/(12*$FrameTimeLength))
Joint#_AngVelDeg=Joint#_AngVel*(180/pi)
Joint#_AngAccDeg=Joint#_AngAcc*(180/pi)
OUTPUT(Joint#_AngVel,Joint#_AngAcc,Joint#_AngVelDeg,Joint#_AngAccDeg)
ENDMACRO


{* =================== *}
{* ORIGIN                    *}
```

```
{* =================== *}

Gorigin={0,0,0}
Global=[Gorigin,{1,0,0},{0,0,1},xyz]
Lnowrap={0,0,0}
Rnowrap={0,0,0}


{* =================== *}
{* OPTIONAL MARKERS     *}
{* =================== *}

OptionalPoints(GLAB,LTEM,RTEM,LMAS,RMAS)
OptionalPoints(CSPN,CLAV,STRN,CHST)
OptionalPoints(LSCS,LSCI,RSCS,RSCI)
OptionalPoints(MPEL,LASI,RASI,LSIS,RSIS)
OptionalPoints(LACR,LHT1,LHT2,LHT3)
OptionalPoints(LELB,LMEL,LRT1,LRT2,LRT3)
OptionalPoints(LRAD,LULN,LFIN,LLFI)
OptionalPoints(RACR,RHT1,RHT2,RHT3)
OptionalPoints(RELB,RMEL,RRT1,RRT2,RRT3)
OptionalPoints(RRAD,RULN,RFIN,RLFI)
OptionalPoints(LFT1,LFT2,LFT3)
OptionalPoints(LKNE,LMKN,LTT1,LTT2,LTT3)
OptionalPoints(LANK,LMAN,LTOE,LLTO)
OptionalPoints(RFT1,RFT2,RFT3)
OptionalPoints(RKNE,RMKN,RTT1,RTT2,RTT3)
OptionalPoints(RANK,RMAN,RTOE,RLTO)
OptionalPoints(HEDCM,THRCM,PELCM,LHUCM,LRACM,LHACM,RHUCM,RRA
CM,RHACM,LFECM,LTICM,LFOCM,RFECM,RTICM,RFOCM,WBCOM)


{* =================== *}
{* HEADSEGMENT            *}
{* =================== *}

FHED=(LTEM+RTEM)/2
BHED=(LMAS+RMAS)/2
LHED=(LTEM+LMAS)/2
RHED=(RTEM+RMAS)/2

{*Head CoM *}
HEDCM=(GLAB+LMAS+RMAS)/3
```

```
OUTPUT(HEDCM)

Head=[HEDCM,LMAS-RMAS,FHED-BHED,yzx]
AXISVISUALISATION(Head)

If $Static==1
        $HeadSize=DIST(FHED,BHED)

{*Create a head offset angle from static trial*}
        $HeadOffset =<Global,Head,xyz>
        PARAM($HeadOffset,$HeadSize)

EndIf
Head=ROT(Head,Head(2),$HeadOffset(2))

HeadSize=$HeadSize
HeadScale={1.4,1.4,1.4}
HeadShift={0,0,0}


{* ===================== *}
{* THORACIC SPINE SEGMENT *}
{* ===================== *}

LSID=(LSIS+RSIS)/2
OUTPUT(LSID)

{*Trunk CoM *}
THRCM=(CSPN-LSID)*0.63+LSID {* Ref: Dempster, 1955; Winter, 1990; Pitt,
1997 *}
OUTPUT(THRCM)

Thorax=[THRCM,STRN-THRCM,LACR-RACR,xzy]
AXISVISUALISATION(Thorax)

If $Static==1 Then
        $ThoraxSize=DIST(LACR,RACR)/2
        PARAM($ThoraxSize)
EndIf

ThoraxSize=0.9*$ThoraxSize
ThoraxScale={1.2,1.2,1.2}
ThoraxShift={0,0,0}
```

```
{* ============================ *}
{* CERVICAL SPINE SEGMENT         *}
{* ============================ *}

CSPine=[(CSPN+CLAV)/2,LACR-RACR,CLAV-CSPN,yzx]
AXISVISUALISATION(CSpine)

CSpineSize=0.5*$ThoraxSize
PARAM(CSpineSize)
CSpineScale={0.8,0.8,0.8}
CSpineShift={0,0,0}


{* ============================ *}
{* PELVIS AND HIP JOINT CENTERS   *}
{* ============================ *}

PelvisTemp=[LSID,LSIS-RSIS,MPEL-LSID,yzx]

{* Define Asis-Trochanter Dist (ATD) as function of leg length *}
LegLength=$LegLength
LATD=0.1288*Leglength-48.56
RATD=LATD

If $InterAsisDistance ==0 Then
    InterAsisDist=DIST(LASI,RASI)
Else
    InterAsisDist=$InterAsisDistance
EndIf

{* Parameters used to work out position of hip joint centres (Davis)*}
C =(LegLength)*0.115-15.3
aa=InterAsisDist/2
mm=($MarkerDiameter+$MarkerExtension)/2
COSBETA=cos(18)
SINBETA=sin(18)
COSTHETA=cos(28.4)
SINTHETA=sin(28.4)

LHJC = {C*COSTHETA*SINBETA-(LATD+mm)*COSBETA,
      -C*SINTHETA+ aa,
      -C*COSTHETA*COSBETA-(LATD+mm)*SINBETA}*PelvisTemp
RHJC = {C*COSTHETA*SINBETA-(RATD+mm)*COSBETA,
```

```
        C*SINTHETA- aa,
       -C*COSTHETA*COSBETA-(RATD+mm)*SINBETA}*PelvisTemp
OUTPUT(LHJC,RHJC)

{* Pelvis CoM *}
PELV=(LHJC+RHJC)/2
PELCM=(LSID-PELV)*0.135+PELV {* Ref: Dempster, 1955; Winter, 1990; Pitt,
1997 *}
OUTPUT(PELCM)

Pelvis=[PELCM,LSIS-RSIS,MPEL-LSID,yzx]
AXISVISUALISATION(Pelvis)

If $Static==1 Then
        $PelvisSize=DIST(LHJC,RHJC)
        PARAM($PelvisSize)
EndIf

PelvisSize=$PelvisSize
PelvisScale={0.8,0.8,0.8}
PelvisShift={0,0,0}

{* HipJoints *}
LHipJoint=LHJC+Attitude(Pelvis)
RHipJoint=RHJC+Attitude(Pelvis)

{* Sacrum *}
SAC0=MPEL+$PelvisSize*{-1,0,0}*Attitude(Pelvis)
Sacrum=SAC0+Attitude(Pelvis)

SacrumSize=PelvisSize/2
PARAM(SacrumSize)
SacrumScale={1,1,1}
SacrumShift={0,0,0}


{* ============================ *}
{* SHOULDER JOINT CENTERS         *}
{* ============================ *}

ShoulderOffset=30
MarkerExtension={0,0,($MarkerDiameter/2)+$MarkerExtension}*Attitude(Thorax)
LSJC=LACR-MarkerExtension-ShoulderOffset*($Stature/1760)*Thorax(3)
```

```
RSJC=RACR-MarkerExtension-ShoulderOffset*($Stature/1760)*Thorax(3)
OUTPUT(LSJC,RSJC)


{* ============================ *}
{* ELBOW JOINT CENTERS          *}
{* ============================ *}

If $Static==1 Then
        If ExistAtAll(LELB,LMEL) Then
                $LElbowWidth=DIST(LELB,LMEL)
        Else
                $LElbowWidth=$MeanElbowWidth
        EndIf
        If ExistAtAll(RELB,RMEL) Then
                $RElbowWidth=DIST(RELB,RMEL)
        Else
                $RElbowWidth=$MeanElbowWidth
        EndIf
        $ElbowWidth=($LElbowWidth+$RElbowWidth)/2
        PARAM($ElbowWidth)
EndIf
ElbowOffset=($MarkerDiameter+$ElbowWidth)/2
If ExistAtAll(LMEL) Then
        LEJC=(LELB+LMEL)/2
Else
        LEJC=CHORD(ElbowOffset,LELB,LSJC,LHT1)
EndIf

If ExistAtAll(RMEL) Then
        REJC=(RELB+RMEL)/2
Else
        REJC=CHORD(ElbowOffset,RELB,RSJC,RHT1)
EndIf
OUTPUT(LEJC,REJC)


{* ============================ *}
{* WRIST JOINT CENTERS          *}
{* ============================ *}

If $Static==1 Then
        If ExistAtAll(LRAD,LULN) Then
```

```
                $LWristWidth=DIST(LRAD,LULN)
        Else
                $LWristWidth=$MeanWristWidth
        EndIf
        If ExistAtAll(RRAD,RULN) Then
                $RWristWidth=DIST(RRAD,RULN)
        Else
                $RWristWidth=$MeanWristWidth
        EndIf   $WristWidth=($LWristWidth+$RWristWidth)/2
        PARAM($WristWidth)
EndIf
WristOffset=($MarkerDiameter+$MarkerExtension+$WristWidth)/2
If ExistAtAll(LULN) Then
        LWJC=(LRAD+LULN)/2
Else
        LWJC=CHORD(WristOffset,LRAD,LEJC,LRT1)
EndIf

If ExistAtAll(RULN) Then
        RWJC=(RRAD+RULN)/2
Else
        RWJC=CHORD(WristOffset,RRAD,REJC,RRT1)
EndIf
OUTPUT(LWJC,RWJC)


{* ============================ *}
{* CLAVICLE SEGMENTS            *}
{* ============================ *}

LCLCM=(LACR+CLAV)/2
RCLCM=(RACR+CLAV)/2

LClavicle=[LCLCM,LACR-CLAV,LSJC-LACR,zxy]
RClavicle=[RCLCM,RACR-CLAV,RACR-RSJC,zxy]
AXISVISUALISATION(LClavicle)
AXISVISUALISATION(RClavicle)

LClavicleSize=DIST(0(LClavicle),0(Thorax))
LClavicleScale={1,1,1}
LClavicleShift={0,0,0}
RClavicleSize=DIST(0(RClavicle),0(Thorax))
RClavicleScale={1,1,1}
```

```
RClavicleShift={0,0,0}


{* ============================= *}
{* SCAPULA SEGMENTS              *}
{* ============================= *}

LSCCM=(LACR+LSCS+LSCI)/3
RSCCM=(RACR+RSCS+RSCI)/3

LScapula=[LSCCM,LSCS-LSCI,LACR-CSPN,zxy]
RScapula=[RSCCM,RSCS-RSCI,CSPN-RACR,zxy]
AXISVISUALISATION(LScapula)
AXISVISUALISATION(RScapula)

LScapulaSize=DIST(0(LScapula),0(Thorax))
LScapulaScale={1,1,1}
LScapulaShift={0,0,0}
RScapulaSize=DIST(0(RScapula),0(Thorax))
RScapulaScale={1,1,1}
RScapulaShift={0,0,0}


{* ============================= *}
{* HUMERUS SEGMENTS              *}
{* ============================= *}

{* Humerus CoM *}
LHUCM=(LSJC-LEJC)*0.523+LEJC {* de Leva, 1996 *}
RHUCM=(RSJC-REJC)*0.523+REJC
OUTPUT(LHUCM,RHUCM)

LHumerus=[LHUCM,LSJC-LEJC,LELB-LEJC,zxy]
RHumerus=[RHUCM,RSJC-REJC,REJC-RELB,zxy]
AXISVISUALISATION(LHumerus)
AXISVISUALISATION(RHumerus)

LHumerusSize=DIST(0(LHumerus),0(LClavicle))
LHumerusScale={1,1,1}
LHumerusShift={0,0,0}
RHumerusSize=DIST(0(RHumerus),0(RClavicle))
RHumerusScale={1,1,1}
RHumerusShift={0,0,0}
```

```
{* ============================ *}
{* RADIUS SEGMENTS                     *}
{* ============================ *}

{*Radius CoM *}
LRACM=(LEJC-LWJC)*0.543+LWJC {* de Leva, 1996 *}
RRACM=(REJC-RWJC)*0.543+RWJC
OUTPUT(LRACM,RRACM)

LRadius=[LRACM,LEJC-LWJC,LELB-LEJC,zxy]
RRadius=[RRACM,REJC-RWJC,REJC-RELB,zxy]
AXISVISUALISATION(LRadius)
AXISVISUALISATION(RRadius)

LRadiusSize=DIST(0(LRadius),0(LHumerus))
LRadiusScale={0.75,0.75,0.75}
LRadiusShift={0,0,0}
RRadiusSize=DIST(0(RRadius),0(RHumerus))
RRadiusScale={0.75,0.75,0.75}
RRadiusShift={0,0,0}


{* ============================ *}
{* HAND SEGMENTS                       *}
{* ============================ *}

{*Hand CoM *}
L3MC=(LFIN+LLFI)/2
R3MC=(RFIN+RLFI)/2

LHACM=(LWJC-L3MC)*-0.79+LWJC {* de Leva, 1996 *}
RHACM=(RWJC-R3MC)*-0.79+RWJC
OUTPUT(LHACM,RHACM)

LHand=[LHACM,LWJC-LHACM,LWJC-LRAD,zxy]
RHand=[RHACM,RWJC-RHACM,RRAD-RWJC,zxy]
AXISVISUALISATION(LHand)
AXISVISUALISATION(RHand)

If $HandLength==0 AND $Static==1 Then
        $HandLength=0.35*(DIST(LWJC,LEJC)+DIST(RWJC,REJC))
        PARAM($HandLength)
Else
```

```
        HandLength=$HandLength
EndIf

LHandSize=RHandSize=HandLength
LHandScale={1,1,1}
LHandShift={0,0,0}
RHandScale={1,1,1}
RHandShift={0,0,0}


{* ============================= *}
{* KNEE JOINT CENTERS            *}
{* ============================= *}

If $Static==1 Then
        If ExistAtAll(LKNE,LMKN) Then
                $LKneeWidth=DIST(LKNE,LMKN)
        Else
                $LKneeWidth=$MeanKneeWidth
        EndIf
        If ExistAtAll(RKNE,RMKN) Then
                $RKneeWidth=DIST(RKNE,RMKN)
        Else
                $RKneeWidth=$MeanKneeWidth
        EndIf
        $KneeWidth=($LKneeWidth+$RKneeWidth)/2
        PARAM($KneeWidth)
EndIf
KneeOffset=($MarkerDiameter+$KneeWidth)/2
If ExistAtAll(LMKN) Then
        LKJC=(LKNE+LMKN)/2
Else
        LKJC=CHORD(KneeOffset,LKNE,LHJC,LFT1)
EndIf
If ExistAtAll(RMKN) Then
        RKJC=(RKNE+RMKN)/2
Else
        RKJC=CHORD(KneeOffset,RKNE,RHJC,RFT1)
EndIf
OUTPUT(LKJC,RKJC)


{* ============================= *}
```

```
{* ANKLE JOINT CENTERS              *}
{* ============================ *}

If $Static==1 Then
        If ExistAtAll(LANK,LMAN) Then
                $LAnkleWidth=DIST(LANK,LMAN)
        Else
                $LAnkleWidth=$MeanAnkleWidth
        EndIf
        If ExistAtAll(RANK,RMAN) Then
                $RAnkleWidth=DIST(RANK,RMAN)
        Else
                $RAnkleWidth=$MeanAnkleWidth
        EndIf
        $AnkleWidth=($LAnkleWidth+$RAnkleWidth)/2
        PARAM($AnkleWidth)
EndIf
AnkleOffset=($MarkerDiameter+$AnkleWidth)/2
If ExistAtAll(LMAN) Then
        LAJC=(LANK+LMAN)/2
Else
        LAJC=CHORD(AnkleOffset,LANK,LKJC,LTT1)
EndIf
If ExistAtAll(RMAN) Then
        RAJC=(RANK+RMAN)/2
Else
        RAJC=CHORD(AnkleOffset,RANK,RKJC,RTT1)
EndIf
OUTPUT(LAJC,RAJC)


{* ============================ *}
{* FEMUR SEGMENTS                   *}
{* ============================ *}

{*Femur CoM *}
LFECM=(LHJC-LKJC)*0.590+LKJC {* de Leva, 1996 *}
RFECM=(RHJC-RKJC)*0.590+RKJC
OUTPUT(LFECM,RFECM)

LFemur=[LFECM,LHJC-LKJC,LKNE-LKJC,zxy]
RFemur=[RFECM,RHJC-RKJC,RKJC-RKNE,zxy]
AXISVISUALISATION(LFemur)
```

```
AXISVISUALISATION(RFemur)

LFemurSize=DIST(0(LFemur),0(LHipJoint))
LFemurScale={1.8,1.8,1.8}
LFemurShift={0,0,0}
RFemurSize=DIST(0(RFemur),0(RHipJoint))
RFemurScale={1.8,1.8,1.8}
RFemurShift={0,0,0}


{* ============================ *}
{* TIBIA SEGMENTS              *}
{* ============================ *}

{* Tibia CoM *}
LTICM=(LKJC-LAJC)*0.561+LAJC {* de Leva, 1996 *}
RTICM=(RKJC-RAJC)*0.561+RAJC
OUTPUT(LTICM,RTICM)

LTibia=[LTICM,LKJC-LAJC,LKNE-LKJC,zxy]
RTibia=[RTICM,RKJC-RAJC,RKJC-RKNE,zxy]
AXISVISUALISATION(LTibia)
AXISVISUALISATION(RTibia)

LTibiaSize=DIST(0(LTibia),0(LFemur))
LTibiaScale={0.9,0.93,0.93}
LTibiaShift={0,0,0}
RTibiaSize=DIST(0(RTibia),0(RFemur))
RTibiaScale={0.93,0.93,0.93}
RTibiaShift={0,0,0}


{* ============================ *}
{* FOOT SEGMENTS               *}
{* ============================ *}
{* Foot CoM *}
LFOCM=(LAJC-LTOE)*0.5+LTOE
RFOCM=(RAJC-RTOE)*0.5+RTOE
OUTPUT(LFOCM,RFOCM)

LFoot=[LFOCM,LAJC-LTOE,LANK-LAJC,zxy]
RFoot=[RFOCM,RAJC-RTOE,RAJC-RANK,zxy]
AXISVISUALISATION(LFoot)
```

```
AXISVISUALISATION(RFoot)

$FootLength=1.34*(DIST(LTOE,LAJC)+DIST(RTOE,RAJC))/2

LFootSize=RFootSize=0.76*$FootLength
LFootScale={1,1,1}
LFootShift={0,0,0}
RFootScale={1,1,1}
RFootShift={0,0,0}


{* ============================ *}
{* ANTHROPOMETRY                         *}
{* ============================ *}

If $Static==1 Then

{* Segment Lengths *}

HeadNeckLength=$Stature*0.182
TorsoLength=DIST(CSPN,LSID)
PelvisLength=DIST(LSID,PELV)
PARAM(HeadNeckLength,TorsoLength,PelvisLength)

HumerusLength=(DIST(LSJC,LEJC)+DIST(RSJC,REJC))/2
RadiusLength=(DIST(LEJC,LWJC)+DIST(REJC,RWJC))/2
HandLength=$HandLength
PARAM(HumerusLength,RadiusLength,HandLength)

FemurLength=(DIST(LHJC,LKJC)+DIST(RHJC,RKJC))/2
TibiaLength=(DIST(LKJC,LAJC)+DIST(RKJC,RAJC))/2
FootLength=$FootLength
PARAM(FemurLength,TibiaLength,FootLength)


{* Segment Masses - Ref: de Leva, 1996 *}
{* Corrections to normal segment masses offered for duration since SCI - Lloyd,
2005 *}

$HeadMass=$BodyMass*0.0694
$ThoraxMass=$BodyMass*(0.1596+(0.0022*$SCI_duration))
$LumbarMass=$BodyMass*(0.1633+(0.0022*$SCI_duration))
$TorsoMass=$ThoraxMass+$LumbarMass
```

```
$PelvisMass=$BodyMass*(0.1117-(0.0012*$SCI_duration))

$HumerusMass=$BodyMass*(0.0271+(0.0004*$SCI_duration))
$RadiusMass=$BodyMass*(0.0162+(0.0002*$SCI_duration))
$HandMass=$BodyMass*(0.0061+(0.00008*$SCI_duration))

$FemurMass=$BodyMass*(0.1416-(0.0016*$SCI_duration))
$TibiaMass=$BodyMass*(0.0433-(0.0005*$SCI_duration))
$FootMass=$BodyMass*(0.0137-(0.0002*$SCI_duration))

PARAM($HeadMass,$ThoraxMass,$LumbarMass,$TorsoMass,$PelvisMass)
PARAM($HumerusMass,$RadiusMass,$HandMass)
PARAM($FemurMass,$TibiaMass,$FootMass)

$HeadMass%=$HeadMass/$BodyMass
$TorsoMass%=$TorsoMass/$BodyMass
$PelvisMass%=$PelvisMass/$BodyMass
$HumerusMass%=$HumerusMass/$BodyMass
$RadiusMass%=$RadiusMass/$BodyMass
$HandMass%=$HandMass/$BodyMass
$FemurMass%=$FemurMass/$BodyMass
$TibiaMass%=$TibiaMass/$BodyMass
$FootMass%=$FootMass/$BodyMass

PARAM($HeadMass%,$TorsoMass%,$PelvisMass%)
PARAM($HumerusMass%,$RadiusMass%,$HandMass%)
PARAM($FemurMass%,$TibiaMass%,$FootMass%)

EndIf


{* =========================== *}
{* WHOLE BODY CENTER OF MASS *}
{* =========================== *}

{* Computed as a function of CoM for the 12 key body segments, exc. Pelvis *}
WBCOM=($HeadMass%*HEDCM)+($TorsoMass%*THRCM)+($PelvisMass%*P
ELCM)
	+($HumerusMass%*LHUCM)+($HumerusMass%*RHUCM)+($RadiusMas
s%*LRACM)+($RadiusMass%*RRACM)+($HandMass%*LHACM)+($HandMass
%*RHACM)
	+($FemurMass%*LFECM)+($FemurMass%*RFECM)+($TibiaMass%*LTI
CM)+($TibiaMass%*RTICM)+($FootMass%*LFOCM)+($FootMass%*RFOCM)
```

```
OUTPUT(WBCOM)


{* ============================ *}
{* KINEMATICS                              *}
{* ============================ *}

{* Angles presented in order of token- y(flex/ext),x(ab/aduction),z(rotation) *}
{* Neck: Head > Thorax *}
Neck_Angle=-<Head,Thorax,yxz>

{* Spine: Pelvis> Thorax *}
Spine_Angle=-<Pelvis,Thorax,yxz>

{* Clavicle: Thorax> Clavicle *}
LClavicle_Angle=-<Thorax,LClavicle,yxz>
RClavicle_Angle=<Thorax,RClavicle,yxz>(-1)

{* Scapula: Thorax> Scapula *}
LScapula_Angle=-<Thorax,LScapula,yxz>
RScapula_Angle=<Thorax,RScapula,yxz>(-1)

{* Shoulders: Thorax> Humeri *}
LShoulder_Angle=-<Thorax,LHumerus,yxz>
RShoulder_Angle=<Thorax,RHumerus,yxz>(-1)

{* Elbows: Humeri> Radii *}
LElbow_Angle=-<LHumerus,LRadius,yxz>(-1)
RElbow_Angle=-<RHumerus,RRadius,yxz>(-1)

{* Wrists: Radii> Hands *}
LWrist_Angle=<LRadius,LHand,yxz>(-3)
LWrist_Angle=<-LWrist_Angle(1),LWrist_Angle(2),LWrist_Angle(3)>
RWrist_Angle=-<RRadius,RHand,yxz>

{* Hips: Pelvis> Femora *}
LHip_Angle=<Pelvis,LFemur,yxz>
RHip_Angle=-<Pelvis,RFemur,yxz>(-1)

{* Knees: Femora> Tibiae *}
LKnee_Angle=<LFemur,LTibia,yxz>(-1)
RKnee_Angle=-<RFemur,RTibia,yxz>
```

```
{* Ankles: Tibiae> Feet *}
LAA=-<LTibia,LFoot,yxz>
LAnkle_Angle =<-90-1(LAA),-3(LAA),-2(LAA)>
RAA=-<RTibia,RFoot,yxz>
RAnkle_Angle=<-90-1(RAA),3(RAA),2(RAA)>

OUTPUT(Neck_Angle,Spine_Angle)
OUTPUT(LClavicle_Angle,RClavicle_Angle)
OUTPUT(LScapula_Angle,RScapula_Angle)
OUTPUT(LShoulder_Angle,RShoulder_Angle)
OUTPUT(LElbow_Angle,RElbow_Angle)
OUTPUT(LWrist_Angle,RWrist_Angle)
OUTPUT(LHip_Angle,RHip_Angle)
OUTPUT(LKnee_Angle,RKnee_Angle)
OUTPUT(LAnkle_Angle,RAnkle_Angle)


LINVELACC(HEDCM,Head)
LINVELACC(THRCM,Thorax)
LINVELACC(PELCM,Pelvis)
LINVELACC(LHUCM,LHumerus)
LINVELACC(RHUCM,RHumerus)
LINVELACC(LRACM,LRadius)
LINVELACC(RRACM,RRadius)
LINVELACC(LHACM,LHand)
LINVELACC(RHACM,RHand)
LINVELACC(LFECM,LFemur)
LINVELACC(RFECM,RFemur)
LINVELACC(LTICM,LTibia)
LINVELACC(RTICM,RTibia)
LINVELACC(LFOCM,LFoot)
LINVELACC(RFOCM,RFoot)


ANGVELACC(Head,Thorax,Neck)
ANGVELACC(Pelvis,Thorax,LSpine)
ANGVELACC(LClavicle,Thorax,LClav)
ANGVELACC(RClavicle,Thorax,RClav)
ANGVELACC(LScapula,Thorax,LScap)
ANGVELACC(RScapula,Thorax,RScap)
ANGVELACC(LHumerus,Thorax,LShoulder)
ANGVELACC(RHumerus,Thorax,RShoulder)
ANGVELACC(LRadius,LHumerus,LElbow)
```

```
ANGVELACC(RRadius,RHumerus,RElbow)
ANGVELACC(LHand,LRadius,LWrist)
ANGVELACC(RHand,RRadius,RWrist)
ANGVELACC(LFemur,Pelvis,LHip)
ANGVELACC(RFemur,Pelvis,RHip)
ANGVELACC(LTibia,LFemur,LKnee)
ANGVELACC(RTibia,RFemur,RKnee)
ANGVELACC(LFoot,LTibia,LAnkle)
ANGVELACC(RFoot,RTibia,RAnkle)


{* ============================ *}
{* KINETICS                             *}
{* ============================ *}

{* Segment Definitions & Heirarchy - [body,inboard body,mass,COM
position,{Ix,Iy,Iz(axial)}] *}
Head=[Head,Thorax,CSPN,$HeadMass,{0,0,0},$HeadMass*{0.0992,0.0992,0.06
81}]
Thorax=[Thorax,Pelvis,LSID,$ThoraxMass,{0,0,0},$ThoraxMass*{0.0961,0.0961,
0}]
Pelvis=[Pelvis,$PelvisMass,{0,0,0},$PelvisMass*{0.25,0.25,0.09}]
LHumerus=[LHumerus,Thorax,LSJC,$HumerusMass,{0,0,0},$HumerusMass*{0.
0724,0.0724,0.025}]
RHumerus=[RHumerus,Thorax,RSJC,$HumerusMass,{0,0,0},$HumerusMass*{0.
0724,0.0724,0.025}]
LRadius=[LRadius,LHumerus,LEJC,$RadiusMass,{0,0,0},$RadiusMass*{0.0702,
0.0702,0.0146}]
RRadius=[RRadius,RHumerus,REJC,$RadiusMass,{0,0,0},$RadiusMass*{0.070
2,0.0702,0.0146}]
LHand=[LHand,LRadius,LWJC,$HandMass,{0,0,0},$HandMass*{0.0552,0.0552,
0.0339}]
RHand=[RHand,RRadius,RWJC,$HandMass,{0,0,0},$HandMass*{0.0552,0.0552
,0.0339}]
LFemur=[LFemur,Pelvis,LHJC,$FemurMass,{0,0,0},$FemurMass*{0.1082,0.1082
,0.0222}]
RFemur=[RFemur,Pelvis,RHJC,$FemurMass,{0,0,0},$FemurMass*{0.1082,0.108
2,0.0222}]
LTibia=[LTibia,LFemur,LKJC,$TibiaMass,{0,0,0},$TibiaMass*{0.0605,0.0605,0.0
104}]
RTibia=[RTibia,RFemur,RKJC,$TibiaMass,{0,0,0},$TibiaMass*{0.0605,0.0605,0.
0104}]
LFoot=[LFoot,LTibia,LAJC,$FootMass,{0,0,0},$FootMass*{0.06,0.06,0.0154}]
```

```
RFoot=[RFoot,RTibia,RAJC,$FootMass,{0,0,0},$FootMass*{0.06,0.06,0.0154}]


OptionalReactions(ForcePlate1,ForcePlate2,ForcePlate3,ForcePlate4)

If ExistAtAll (ForcePlate1,ForcePlate2,ForcePlate3,ForcePlate4) Then
	TrapezeForce=ForcePlate1(1)
	VanHandleForce=ForcePlate2(1)
	LGloveForce=ForcePlate3(1)
	RGloveForce=ForcePlate4(1)

	LForceDirect=[LHACM,LSJC-LHACM,LRAD-LWJC,zxy]
	RForceDirect=[RHACM,RSJC-RHACM,LWJC-LRAD,zxy]

	LGloveForceNew={LGloveForce(1),LGloveForce(2),LGloveForce(3)}*Attitude(LForceDirect)
	ForcePlate3=|LGloveForceNew,ForcePlate3(2),{LHACM(1),LHACM(2),LHACM(3)}|
	CONNECT(LHand,ForcePlate3,1)

	RGloveForceNew={RGloveForce(1),RGloveForce(2),RGloveForce(3)}*Attitude(RForceDirect)
	ForcePlate4=|RGloveForceNew,ForcePlate4(2),{RHACM(1),RHACM(2),RHACM(3)}|
	CONNECT(RHand,ForcePlate4,1)
EndIf

ReactLWrist=REACTION(LHand)
ReactRWrist=REACTION(RHand)
ReactLElbow=REACTION(LRadius)
ReactRElbow=REACTION(RRadius)
ReactLShoulder=REACTION(LHumerus)
ReactRShoulder=REACTION(RHumerus)
ReactLSID=REACTION(Thorax)
ReactLHip=REACTION(LFemur)
ReactRHip=REACTION(RFemur)
ReactLKnee=REACTION(LTibia)
ReactRKnee=REACTION(RTibia)
ReactLAnkle=REACTION(LFoot)
ReactRAnkle=REACTION(RFoot)

LWrist_F=ReactLWrist(1)
RWrist_F=ReactRWrist(1)
```

```
LElbow_F=ReactLElbow(1)
RElbow_F=ReactRElbow(1)
LShoulder_F=ReactLShoulder(1)
RShoulder_F=ReactRShoulder(1)
Spine_F=ReactLSID(1)
LHip_F=ReactLHip(1)
RHip_F=ReactRHip(1)
LKnee_F=ReactLKnee(1)
RKnee_F=ReactRKnee(1)
LAnkle_F=ReactLAnkle(1)
RAnkle_F=ReactRAnkle(1)

LWrist_Force={SQRT(LWrist_F(1)*LWrist_F(1)),SQRT(LWrist_F(2)*LWrist_F(2)),
SQRT(LWrist_F(3)*LWrist_F(3))}
RWrist_Force={SQRT(RWrist_F(1)*RWrist_F(1)),SQRT(RWrist_F(2)*RWrist_F(2
)),SQRT(RWrist_F(3)*RWrist_F(3))}
LElbow_Force={SQRT(LElbow_F(1)*LElbow_F(1)),SQRT(LElbow_F(2)*LElbow_
F(2)),SQRT(LElbow_F(3)*LElbow_F(3))}
RElbow_Force={SQRT(RElbow_F(1)*RElbow_F(1)),SQRT(RElbow_F(2)*RElbo
w_F(2)),SQRT(RElbow_F(3)*RElbow_F(3))}
LShoulder_Force={SQRT(LShoulder_F(1)*LShoulder_F(1)),SQRT(LShoulder_F(
2)*LShoulder_F(2)),SQRT(LShoulder_F(3)*LShoulder_F(3))}
RShoulder_Force={SQRT(RShoulder_F(1)*RShoulder_F(1)),SQRT(RShoulder_
F(2)*RShoulder_F(2)),SQRT(RShoulder_F(3)*RShoulder_F(3))}
Spine_Force={SQRT(Spine_F(1)*Spine_F(1)),SQRT(Spine_F(2)*Spine_F(2)),S
QRT(Spine_F(3)*Spine_F(3))}
LHip_Force={SQRT(LHip_F(1)*LHip_F(1)),SQRT(LHip_F(2)*LHip_F(2)),SQRT(L
Hip_F(3)*LHip_F(3))}
RHip_Force={SQRT(RHip_F(1)*RHip_F(1)),SQRT(RHip_F(2)*RHip_F(2)),SQRT
(RHip_F(3)*RHip_F(3))}
LKnee_Force={SQRT(LKnee_F(1)*LKnee_F(1)),SQRT(LKnee_F(2)*LKnee_F(2))
,SQRT(LKnee_F(3)*LKnee_F(3))}
RKnee_Force={SQRT(RKnee_F(1)*RKnee_F(1)),SQRT(RKnee_F(2)*RKnee_F(
2)),SQRT(RKnee_F(3)*RKnee_F(3))}
LAnkle_Force={SQRT(LAnkle_F(1)*LAnkle_F(1)),SQRT(LAnkle_F(2)*LAnkle_F(
2)),SQRT(LAnkle_F(3)*LAnkle_F(3))}
RAnkle_Force={SQRT(RAnkle_F(1)*RAnkle_F(1)),SQRT(RAnkle_F(2)*RAnkle_
F(2)),SQRT(RAnkle_F(3)*RAnkle_F(3))}

OUTPUT(LWrist_Force,RWrist_Force,LElbow_Force,RElbow_Force,LShoulder_
Force,RShoulder_Force)
OUTPUT(Spine_Force,LHip_Force,RHip_Force,LKnee_Force,RKnee_Force,LAn
kle_Force,RAnkle_Force)
```

```
LWrist_Moment=ReactLWrist(2)
RWrist_Moment=ReactRWrist(2)
LElbow_Moment=ReactLElbow(2)
RElbow_Moment=ReactRElbow(2)
LShoulder_Moment=ReactLShoulder(2)
RShoulder_Moment=ReactRShoulder(2)
Spine_Moment=ReactLSID(2)
LHip_Moment=ReactLHip(2)
RHip_Moment=ReactRHip(2)
LKnee_Moment=ReactLKnee(2)
RKnee_Moment=ReactRKnee(2)
LAnkle_Moment=ReactLAnkle(2)
RAnkle_Moment=ReactRAnkle(2)

OUTPUT(LWrist_Moment,RWrist_Moment,LElbow_Moment,RElbow_Moment,L
Shoulder_Moment,RShoulder_Moment)
OUTPUT(Spine_Moment,LHip_Moment,RHip_Moment,LKnee_Moment,RKnee_
Moment,LAnkle_Moment,RAnkle_Moment)


LWrist_Power=POWER(LRadius,LHand)
RWrist_Power=POWER(RRadius,RHand)
LElbow_Power=POWER(LHumerus,LRadius)
RElbow_Power=POWER(RHumerus,RRadius)
LShoulder_Power=POWER(Thorax,LHumerus)
RShoulder_Power=POWER(Thorax,RHumerus)
Spine_Power=POWER(Thorax,Pelvis)
LHip_Power=POWER(Pelvis,LFemur)
RHip_Power=POWER(Pelvis,RFemur)
LKnee_Power=POWER(LFemur,LTibia)
RKnee_Power=POWER(RFemur,RTibia)
LAnkle_Power=POWER(LTibia,LFoot)
RAnkle_Power=POWER(RTibia,RFoot)

OUTPUT(LWrist_Power,RWrist_Power,LElbow_Power,RElbow_Power,LShoulde
r_Power,RShoulder_Power)
OUTPUT(Spine_Power,LHip_Power,RHip_Power,LKnee_Power,RKnee_Power,
LAnkle_Power,RAnkle_Power)


{* ============================= *}
{* END OF MODEL                  *}
{* ============================= *}
```

```
{*
=============================================================
=========== *}
                 Whole-body biomechanical model for
       3D dynamic kinematic and kinetic analysis of human motion
                                2005
                         John D Lloyd, Ph.D.
             VA Patient Safety Research Center, Tampa, Florida
{*
=============================================================
=========== *}

{*
=============================================================
=========== *}
                    PART 3 - POLYGON & SCALING
                                 {*
=============================================================
                          =========== *}


{* =========================== *}
{* MACROS                     *}
{* =========================== *}

macro DRAWBONE(Bone,BoneLabel)
{*Outputs segment definition markers in Polygon format *}
LL=Bone#Size
DD=LL/10
WW=DD
BoneLabel#O=0(Bone)+LL*Bone#Shift*Attitude(Bone)
BoneLabel#P=BoneLabel#O+LL*3(Bone#Scale)*3(Bone)
BoneLabel#A=BoneLabel#O+DD*1(Bone#Scale)*1(Bone)
BoneLabel#L=BoneLabel#O+WW*2(Bone#Scale)*2(Bone)
OUTPUT(BoneLabel#O,BoneLabel#P,BoneLabel#A,BoneLabel#L)
ENDMACRO

{* ========== *}

macro RESIZE(Segment)
{*Segment scale and shift*}
Segment#Axes=[Segment#O,Segment#P-Segment#O,Segment#L-
Segment#O,zxy]
```

```
Segment#O = Segment#O + ($Shift#Segment*Attitude(Segment#Axes))
Segment#P = Segment#P + ($Shift#Segment*Attitude(Segment#Axes))
Segment#A = Segment#A + ($Shift#Segment*Attitude(Segment#Axes))
Segment#L = Segment#L + ($Shift#Segment*Attitude(Segment#Axes))
Segment#Axes=[Segment#O,Segment#P-Segment#O,Segment#L-
Segment#O,zxy]
Segment#P =
{0,0,($PSize#Segment*DIST(Segment#P,Segment#O))}*Segment#Axes
Segment#A =
{($AAxisLength#Segment*DIST(Segment#A,Segment#O)),0,0}*Segment#Axes
Segment#L =
{0,($LAxisLength#Segment*DIST(Segment#L,Segment#O)),0}*Segment#Axes
OUTPUT(Segment#O,Segment#P,Segment#A,Segment#L)
ENDMACRO

{* ========== *}

macro ATTACH1(Attachment,Bone)
{*Attaches Left and Right muscles to one mid-line bone *}
L#Attachment =      {(1(Attachment)+1(Bone#Shift))*1(Bone#Scale),
                     (2(Attachment)+2(Bone#Shift))*2(Bone#Scale),
                     (3(Attachment)+3(Bone#Shift))*3(Bone#Scale)}*Bone#Size*Bone
R#Attachment =      {(1(Attachment)+1(Bone#Shift))*1(Bone#Scale),
                    -(2(Attachment)+2(Bone#Shift))*2(Bone#Scale),
                     (3(Attachment)+3(Bone#Shift))*3(Bone#Scale)}*Bone#Size*Bone
ENDMACRO

{* ========== *}

macro ATTACH2(Attachment,Bone)
{*Attaches Left and Right muscles to Left and Right bones *}
L#Attachment =      {(1(Attachment)+1(L#Bone#Shift))*1(L#Bone#Scale),
                     (2(Attachment)+2(L#Bone#Shift))*2(L#Bone#Scale),

(3(Attachment)+3(L#Bone#Shift))*3(L#Bone#Scale)}*L#Bone#Size*L#Bone
R#Attachment =      {(1(Attachment)+1(R#Bone#Shift))*1(R#Bone#Scale),
                    -(2(Attachment)+2(R#Bone#Shift))*2(R#Bone#Scale),

(3(Attachment)+3(R#Bone#Shift))*3(R#Bone#Scale)}*R#Bone#Size*R#Bone
ENDMACRO

{* ========== *}
```

```
macro DRAWMUSCLE(Muscle,Origin,Insertion,wrap1,wrap2)
{*Outputs muscle length, origin, instertion, and up to 2 "wrap points" *}
If DIST(L#wrap1,{0,0,0})>= 0.0001 Then
        If DIST(L#wrap2,{0,0,0})>= 0.0001 Then

        L#Muscle#Length=DIST(L#Origin,L#wrap1)+DIST(L#wrap1,L#wrap2)+DI
ST(L#wrap2,L#Insertion)
                OUTPUT(L#wrap1,L#wrap2)
        Else

        L#Muscle#Length=DIST(L#Origin,L#wrap1)+DIST(L#wrap1,L#Insertion)
                OUTPUT(L#wrap1)
        EndIf
Else
        L#Muscle#Length=DIST(L#Origin,L#Insertion)
EndIf

If DIST(R#wrap1,{0,0,0})>= 0.0001 Then
        If DIST(R#wrap2,{0,0,0})>= 0.0001 Then

        R#Muscle#Length=DIST(R#Origin,R#wrap1)+DIST(R#wrap1,R#wrap2)+D
IST(R#wrap2,R#Insertion)
                OUTPUT(R#wrap1,R#wrap2)
        Else

        R#Muscle#Length=DIST(R#Origin,R#wrap1)+DIST(R#wrap1,R#Insertion)
                OUTPUT(R#wrap1)
        EndIf
Else
        R#Muscle#Length=DIST(R#Origin,R#Insertion)
EndIf

If $MuscleLengthsOutput ==1 Then
        OUTPUT(L#Origin,L#Insertion,L#Muscle#Length)
        OUTPUT(R#Origin,R#Insertion,R#Muscle#Length)
Else
        OUTPUT(L#Origin,L#Insertion)
        OUTPUT(R#Origin,R#Insertion)
EndIf
ENDMACRO


{* =================== *}
```

```
{* ORIGIN               *}
{* ==================== *}

Gorigin={0,0,0}
Global=[Gorigin,{1,0,0},{0,0,1},xyz]
Lnowrap={0,0,0}
Rnowrap={0,0,0}


{* ==================== *}
{* OPTIONAL MARKERS     *}
{* ==================== *}

OptionalPoints(GLAB,LTEM,RTEM,LMAS,RMAS)
OptionalPoints(CSPN,CLAV,STRN,CHST)
OptionalPoints(LSCS,LSCI,RSCS,RSCI)
OptionalPoints(MPEL,LASI,RASI,LSIS,RSIS)
OptionalPoints(LACR,LHT1,LHT2,LHT3)
OptionalPoints(LELB,LMEL,LRT1,LRT2,LRT3)
OptionalPoints(LRAD,LULN,LFIN,LLFI)
OptionalPoints(RACR,RHT1,RHT2,RHT3)
OptionalPoints(RELB,RMEL,RRT1,RRT2,RRT3)
OptionalPoints(RRAD,RULN,RFIN,RLFI)
OptionalPoints(LFT1,LFT2,LFT3)
OptionalPoints(LKNE,LMKN,LTT1,LTT2,LTT3)
OptionalPoints(LANK,LMAN,LTOE,LLTO)
OptionalPoints(RFT1,RFT2,RFT3)
OptionalPoints(RKNE,RMKN,RTT1,RTT2,RTT3)
OptionalPoints(RANK,RMAN,RTOE,RLTO)
OptionalPoints(HEDCM,THRCM,PELCM,LHUCM,LRACM,LHACM,RHUCM,RRA
CM,RHACM,LFECM,LTICM,LFOCM,RFECM,RTICM,RFOCM,WBCOM)


{* ==================== *}
{* HEADSEGMENT          *}
{* ==================== *}

FHED=(LTEM+RTEM)/2
BHED=(LMAS+RMAS)/2
LHED=(LTEM+LMAS)/2
RHED=(RTEM+RMAS)/2

{*Head CoM *}
```

```
HEDCM=(GLAB+LMAS+RMAS)/3
OUTPUT(HEDCM)

Head=[HEDCM,LMAS-RMAS,FHED-BHED,yzx]

If $Static==1
        $HeadSize=DIST(FHED,BHED)

{*Create a head offset angle from static trial*}
        $HeadOffset =<Global,Head,xyz>
        PARAM($HeadOffset,$HeadSize)

EndIf
Head=ROT(Head,Head(2),$HeadOffset(2))

HeadSize=$HeadSize
HeadScale={1.4,1.4,1.4}
HeadShift={0,0,0}


{* ====================== *}
{* THORACIC SPINE SEGMENT *}
{* ====================== *}

LSID=(LSIS+RSIS)/2
OUTPUT(LSID)

{*Trunk CoM *}
THRCM=(CSPN-LSID)*0.63+LSID {* Ref: Dempster, 1955; Winter, 1990; Pitt,
1997 *}
OUTPUT(THRCM)

Thorax=[THRCM,STRN-THRCM,LACR-RACR,xzy]

If $Static==1 Then
        $ThoraxSize=DIST(LACR,RACR)/2
        PARAM($ThoraxSize)
EndIf

ThoraxSize=0.9*$ThoraxSize
ThoraxScale={1.2,1.2,1.2}
ThoraxShift={0,0,0}
```

```
{* ============================ *}
{* CERVICAL SPINE SEGMENT         *}
{* ============================ *}

CSPine=[(CSPN+CLAV)/2,LACR-RACR,CLAV-CSPN,yzx]

CSpineSize=0.5*$ThoraxSize
PARAM(CSpineSize)
CSpineScale={0.8,0.8,0.8}
CSpineShift={0,0,0}


{* ============================ *}
{* PELVIS AND HIP JOINT CENTERS   *}
{* ============================ *}

PelvisTemp=[LSID,LSIS-RSIS,MPEL-LSID,yzx]

{* Define Asis-Trochanter Dist (ATD) as function of leg length *}
LegLength=$LegLength
LATD=0.1288*Leglength-48.56
RATD=LATD

If $InterAsisDistance ==0 Then
    InterAsisDist=DIST(LASI,RASI)
Else
    InterAsisDist=$InterAsisDistance
EndIf

{* Parameters used to work out position of hip joint centres (Davis)*}
C =(LegLength)*0.115-15.3
aa=InterAsisDist/2
mm=($MarkerDiameter+$MarkerExtension)/2
COSBETA=cos(18)
SINBETA=sin(18)
COSTHETA=cos(28.4)
SINTHETA=sin(28.4)

LHJC = {C*COSTHETA*SINBETA-(LATD+mm)*COSBETA,
      -C*SINTHETA+ aa,
      -C*COSTHETA*COSBETA-(LATD+mm)*SINBETA}*PelvisTemp
RHJC = {C*COSTHETA*SINBETA-(RATD+mm)*COSBETA,
```

```
        C*SINTHETA- aa,
       -C*COSTHETA*COSBETA-(RATD+mm)*SINBETA}*PelvisTemp
OUTPUT(LHJC,RHJC)

{* Pelvis CoM *}
PELV=(LHJC+RHJC)/2
PELCM=(LSID-PELV)*0.135+PELV {* Ref: Dempster, 1955; Winter, 1990; Pitt,
1997 *}
OUTPUT(PELCM)

Pelvis=[PELCM,LSIS-RSIS,MPEL-LSID,yzx]

If $Static==1 Then
        $PelvisSize=DIST(LHJC,RHJC)
        PARAM($PelvisSize)
EndIf

PelvisSize=$PelvisSize
PelvisScale={0.8,0.8,0.8}
PelvisShift={0,0,0}

{* HipJoints *}
LHipJoint=LHJC+Attitude(Pelvis)
RHipJoint=RHJC+Attitude(Pelvis)

{* Sacrum *}
SAC0=MPEL+$PelvisSize*{-1,0,0}*Attitude(Pelvis)
Sacrum=SAC0+Attitude(Pelvis)

SacrumSize=PelvisSize/2
PARAM(SacrumSize)
SacrumScale={1,1,1}
SacrumShift={0,0,0}


{* ============================ *}
{* SHOULDER JOINT CENTERS        *}
{* ============================ *}

ShoulderOffset=30
MarkerExtension={0,0,($MarkerDiameter/2)+$MarkerExtension}*Attitude(Thorax)
LSJC=LACR-MarkerExtension-ShoulderOffset*($Stature/1760)*Thorax(3)
RSJC=RACR-MarkerExtension-ShoulderOffset*($Stature/1760)*Thorax(3)
```

```
OUTPUT(LSJC,RSJC)


{* ============================ *}
{* ELBOW JOINT CENTERS            *}
{* ============================ *}

If $Static==1 Then
        If ExistAtAll(LELB,LMEL) Then
                $LElbowWidth=DIST(LELB,LMEL)
        Else
                $LElbowWidth=$MeanElbowWidth
        EndIf
        If ExistAtAll(RELB,RMEL) Then
                $RElbowWidth=DIST(RELB,RMEL)
        Else
                $RElbowWidth=$MeanElbowWidth
        EndIf
        $ElbowWidth=($LElbowWidth+$RElbowWidth)/2
        PARAM($ElbowWidth)
EndIf
ElbowOffset=($MarkerDiameter+$ElbowWidth)/2
If ExistAtAll(LMEL) Then
        LEJC=(LELB+LMEL)/2
Else
        LEJC=CHORD(ElbowOffset,LELB,LSJC,LHT1)
EndIf

If ExistAtAll(RMEL) Then
        REJC=(RELB+RMEL)/2
Else
        REJC=CHORD(ElbowOffset,RELB,RSJC,RHT1)
EndIf
OUTPUT(LEJC,REJC)


{* ============================ *}
{* WRIST JOINT CENTERS            *}
{* ============================ *}

If $Static==1 Then
        If ExistAtAll(LRAD,LULN) Then
                $LWristWidth=DIST(LRAD,LULN)
```

```
		Else
			$LWristWidth=$MeanWristWidth
		EndIf
		If ExistAtAll(RRAD,RULN) Then
			$RWristWidth=DIST(RRAD,RULN)
		Else
			$RWristWidth=$MeanWristWidth
		EndIf	$WristWidth=($LWristWidth+$RWristWidth)/2
		PARAM($WristWidth)
EndIf
WristOffset=($MarkerDiameter+$MarkerExtension+$WristWidth)/2
If ExistAtAll(LULN) Then
		LWJC=(LRAD+LULN)/2
Else
		LWJC=CHORD(WristOffset,LRAD,LEJC,LRT1)
EndIf

If ExistAtAll(RULN) Then
		RWJC=(RRAD+RULN)/2
Else
		RWJC=CHORD(WristOffset,RRAD,REJC,RRT1)
EndIf
OUTPUT(LWJC,RWJC)


{* ============================ *}
{* CLAVICLE SEGMENTS                  *}
{* ============================ *}

LCLCM=(LACR+CLAV)/2
RCLCM=(RACR+CLAV)/2

LClavicle=[LCLCM,LACR-CLAV,LSJC-LACR,zxy]
RClavicle=[RCLCM,RACR-CLAV,RACR-RSJC,zxy]

LClavicleSize=DIST(0(LClavicle),0(Thorax))
LClavicleScale={1,1,1}
LClavicleShift={0,0,0}
RClavicleSize=DIST(0(RClavicle),0(Thorax))
RClavicleScale={1,1,1}
RClavicleShift={0,0,0}

{* ============================ *}
```

```
{* SCAPULA SEGMENTS            *}
{* ============================ *}

LSCCM=(LACR+LSCS+LSCI)/3
RSCCM=(RACR+RSCS+RSCI)/3

LScapula=[LSCCM,LSCS-LSCI,LACR-CSPN,zxy]
RScapula=[RSCCM,RSCS-RSCI,CSPN-RACR,zxy]

LScapulaSize=DIST(0(LScapula),0(Thorax))
LScapulaScale={1,1,1}
LScapulaShift={0,0,0}
RScapulaSize=DIST(0(RScapula),0(Thorax))
RScapulaScale={1,1,1}
RScapulaShift={0,0,0}


{* ============================ *}
{* HUMERUS SEGMENTS             *}
{* ============================ *}

{* Humerus CoM *}
LHUCM=(LSJC-LEJC)*0.523+LEJC {* de Leva, 1996 *}
RHUCM=(RSJC-REJC)*0.523+REJC
OUTPUT(LHUCM,RHUCM)

LHumerus=[LHUCM,LSJC-LEJC,LELB-LEJC,zxy]
RHumerus=[RHUCM,RSJC-REJC,REJC-RELB,zxy]

LHumerusSize=DIST(0(LHumerus),0(LClavicle))
LHumerusScale={1,1,1}
LHumerusShift={0,0,0}
RHumerusSize=DIST(0(RHumerus),0(RClavicle))
RHumerusScale={1,1,1}
RHumerusShift={0,0,0}


{* ============================ *}
{* RADIUS SEGMENTS              *}
{* ============================ *}

{*Radius CoM *}
LRACM=(LEJC-LWJC)*0.543+LWJC {* de Leva, 1996 *}
```

```
RRACM=(REJC-RWJC)*0.543+RWJC
OUTPUT(LRACM,RRACM)

LRadius=[LRACM,LEJC-LWJC,LELB-LEJC,zxy]
RRadius=[RRACM,REJC-RWJC,REJC-RELB,zxy]

LRadiusSize=DIST(0(LRadius),0(LHumerus))
LRadiusScale={0.75,0.75,0.75}
LRadiusShift={0,0,0}
RRadiusSize=DIST(0(RRadius),0(RHumerus))
RRadiusScale={0.75,0.75,0.75}
RRadiusShift={0,0,0}


{* ============================ *}
{* HAND SEGMENTS                  *}
{* ============================ *}

{*Hand CoM *}
L3MC=(LFIN+LLFI)/2
R3MC=(RFIN+RLFI)/2

LHACM=(LWJC-L3MC)*-0.79+LWJC {* de Leva, 1996 *}
RHACM=(RWJC-R3MC)*-0.79+RWJC
OUTPUT(LHACM,RHACM)

LHand=[LHACM,LWJC-LHACM,LWJC-LRAD,zxy]
RHand=[RHACM,RWJC-RHACM,RRAD-RWJC,zxy]

If $HandLength==0 AND $Static==1 Then
        $HandLength=0.35*(DIST(LWJC,LEJC)+DIST(RWJC,REJC))
        PARAM($HandLength)
Else
        HandLength=$HandLength
EndIf

LHandSize=RHandSize=HandLength
LHandScale={1,1,1}
LHandShift={0,0,0}
RHandScale={1,1,1}
RHandShift={0,0,0}

{* ============================ *}
```

```
{* KNEE JOINT CENTERS                *}
{* ============================ *}

If $Static==1 Then
        If ExistAtAll(LKNE,LMKN) Then
                $LKneeWidth=DIST(LKNE,LMKN)
        Else
                $LKneeWidth=$MeanKneeWidth
        EndIf
        If ExistAtAll(RKNE,RMKN) Then
                $RKneeWidth=DIST(RKNE,RMKN)
        Else
                $RKneeWidth=$MeanKneeWidth
        EndIf
        $KneeWidth=($LKneeWidth+$RKneeWidth)/2
        PARAM($KneeWidth)
EndIf
KneeOffset=($MarkerDiameter+$KneeWidth)/2
If ExistAtAll(LMKN) Then
        LKJC=(LKNE+LMKN)/2
Else
        LKJC=CHORD(KneeOffset,LKNE,LHJC,LFT1)
EndIf
If ExistAtAll(RMKN) Then
        RKJC=(RKNE+RMKN)/2
Else
        RKJC=CHORD(KneeOffset,RKNE,RHJC,RFT1)
EndIf
OUTPUT(LKJC,RKJC)


{* ============================ *}
{* ANKLE JOINT CENTERS               *}
{* ============================ *}

If $Static==1 Then
        If ExistAtAll(LANK,LMAN) Then
                $LAnkleWidth=DIST(LANK,LMAN)
        Else
                $LAnkleWidth=$MeanAnkleWidth
        EndIf
        If ExistAtAll(RANK,RMAN) Then
                $RAnkleWidth=DIST(RANK,RMAN)
```

```
        Else
                $RAnkleWidth=$MeanAnkleWidth
        EndIf
        $AnkleWidth=($LAnkleWidth+$RAnkleWidth)/2
        PARAM($AnkleWidth)
EndIf
AnkleOffset=($MarkerDiameter+$AnkleWidth)/2
If ExistAtAll(LMAN) Then
        LAJC=(LANK+LMAN)/2
Else
        LAJC=CHORD(AnkleOffset,LANK,LKJC,LTT1)
EndIf
If ExistAtAll(RMAN) Then
        RAJC=(RANK+RMAN)/2
Else
        RAJC=CHORD(AnkleOffset,RANK,RKJC,RTT1)
EndIf
OUTPUT(LAJC,RAJC)


{* ============================ *}
{* FEMUR SEGMENTS               *}
{* ============================ *}

{*Femur CoM *}
LFECM=(LHJC-LKJC)*0.590+LKJC {* de Leva, 1996 *}
RFECM=(RHJC-RKJC)*0.590+RKJC
OUTPUT(LFECM,RFECM)

LFemur=[LFECM,LHJC-LKJC,LKNE-LKJC,zxy]
RFemur=[RFECM,RHJC-RKJC,RKJC-RKNE,zxy]

LFemurSize=DIST(0(LFemur),0(LHipJoint))
LFemurScale={1.8,1.8,1.8}
LFemurShift={0,0,0}
RFemurSize=DIST(0(RFemur),0(RHipJoint))
RFemurScale={1.8,1.8,1.8}
RFemurShift={0,0,0}


{* ============================ *}
{* TIBIA SEGMENTS               *}
{* ============================ *}
```

```
{* Tibia CoM *}
LTICM=(LKJC-LAJC)*0.561+LAJC {* de Leva, 1996 *}
RTICM=(RKJC-RAJC)*0.561+RAJC
OUTPUT(LTICM,RTICM)

LTibia=[LTICM,LKJC-LAJC,LKNE-LKJC,zxy]
RTibia=[RTICM,RKJC-RAJC,RKJC-RKNE,zxy]

LTibiaSize=DIST(0(LTibia),0(LFemur))
LTibiaScale={0.9,0.93,0.93}
LTibiaShift={0,0,0}
RTibiaSize=DIST(0(RTibia),0(RFemur))
RTibiaScale={0.93,0.93,0.93}
RTibiaShift={0,0,0}


{* ============================ *}
{* FOOT SEGMENTS                *}
{* ============================ *}
{* Foot CoM *}
LFOCM=(LAJC-LTOE)*0.5+LTOE
RFOCM=(RAJC-RTOE)*0.5+RTOE
OUTPUT(LFOCM,RFOCM)

LFoot=[LFOCM,LAJC-LTOE,LANK-LAJC,zxy]
RFoot=[RFOCM,RAJC-RTOE,RAJC-RANK,zxy]

$FootLength=1.34*(DIST(LTOE,LAJC)+DIST(RTOE,RAJC))/2

LFootSize=RFootSize=0.76*$FootLength
LFootScale={1,1,1}
LFootShift={0,0,0}
RFootScale={1,1,1}
RFootShift={0,0,0}


{* ============================ *}
{* DRAW BONES                   *}
{* ============================ *}

DrawBone(Head,HEADbone_)
DrawBone(CSpine,CSPINEbone_)
DrawBone(Thorax,THORAXbone_)
```

```
DrawBone(Pelvis,PELVISbone_)
DrawBone(Sacrum,SACRUMbone_)
DrawBone(LClavicle,LCLAVbone_)
DrawBone(RClavicle,RCLAVbone_)
DrawBone(LHumerus,LHUMbone_)
DrawBone(RHumerus,RHUMbone_)
DrawBone(LRadius,LRADbone_)
DrawBone(RRadius,RRADbone_)
DrawBone(LHand,LHANDbone_)
DrawBone(RHand,RHANDbone_)
DrawBone(LFemur,LFEMURbone_)
DrawBone(RFemur,RFEMURbone_)
DrawBone(LTibia,LTIBIAbone_)
DrawBone(RTibia,RTIBIAbone_)
DrawBone(LFoot,LFOOTbone_)
DrawBone(RFoot,RFOOTbone_)


{* ============================ *}
{* RESIZE BONE SEGMENTS           *}
{* ============================ *}

RESIZE(HEADbone_)
RESIZE(CSPINEbone_)
RESIZE(THORAXbone_)
RESIZE(PELVISbone_)
RESIZE(SACRUMbone_)
RESIZE(LCLAVbone_)
RESIZE(RCLAVbone_)
RESIZE(LHUMbone_)
RESIZE(RHUMbone_)
RESIZE(LRADbone_)
RESIZE(RRADbone_)
RESIZE(LHANDbone_)
RESIZE(RHANDbone_)
RESIZE(LFEMURbone_)
RESIZE(RFEMURbone_)
RESIZE(LTIBIAbone_)
RESIZE(RTIBIAbone_)
RESIZE(LFOOTbone_)
RESIZE(RFOOTbone_)

{* ============================ *}
```

```
{* ATTACH MUSCLES                    *}
{* ============================= *}

Attach1(MastoidProcess,Head)
Attach1(Occiput,Head)

Attach1(PostT1,Thorax)
Attach1(PostT7,Thorax)
Attach1(MidSternum,Thorax)
Attach1(AntT12,Thorax)

Attach1(IliacCrest,Pelvis)
Attach1(IliacFossa,Pelvis)
Attach1(AntInfIliacSpine,Pelvis)
Attach1(PelvicBrim,Pelvis)
Attach1(PostSacrum,Pelvis)
Attach1(IschialTuberosity,Pelvis)

Attach2(LatClavicle,Clavicle)
Attach2(MedClavicle,Clavicle)
Attach2(SupraGlenoidTubercle,Clavicle)

Attach2(UppAntHumerus,Humerus)
Attach2(UppPostHumerus,Humerus)
Attach2(LowAntHumerus,Humerus)
Attach2(LowLatHumerus,Humerus)
Attach2(MedHumeralEpicondyle,Humerus)
Attach2(LatHumeralEpicondyle,Humerus)

Attach2(UlnarOlecranon,Radius)
Attach2(UlnarTuberosity,Radius)
Attach2(RadialTuberosity,Radius)
Attach2(UppMedUlna,Radius)
Attach2(MidLatRadius,Radius)
Attach2(LowLatRadius,Radius)
Attach2(FlexorRetinaculum,Radius)
Attach2(ExtensorRetinaculum,Radius)

Attach2(Pal2MetaCarpal,Hand)
Attach2(Pal5MetaCarpal,Hand)
Attach2(Pal3DistalPhalanx,Hand)
Attach2(Dor3DistalPhalanx,Hand)
```

```
Attach2(GreaterTrochanter,Femur)
Attach2(LesserTrochanter,Femur)
Attach2(UppFemoralShaft,Femur)
Attach2(MidFemoralShaft,Femur)
Attach2(LatFemoralCondyle,Femur)
Attach2(MedFemoralCondyle,Femur)
Attach2(Patella,Femur)

Attach2(MedTibialCondyle,Tibia)
Attach2(UppLatTibia,Tibia)
Attach2(HeadFibula,Tibia)
Attach2(TibialTubercle,Tibia)
Attach2(MidFibula,Tibia)
Attach2(InfExtensorRetinaculum,Tibia)

Attach2(Calcaneous,Foot)
Attach2(MedCuneiform,Foot)


{* ============================ *}
{* DRAW MUSCLES                 *}
{* ============================ *}

DrawMuscle(UppTrapezius,Occiput,LatClavicle,nowrap,nowrap)
DrawMuscle(UppSpleniusCapitis,MastoidProcess,PostT1,nowrap,nowrap)
DrawMuscle(SternoMastoid,MastoidProcess,MedClavicle,nowrap,nowrap)

DrawMuscle(BicepsBrachii,SupraGlenoidTubercle,RadialTuberosity,nowrap,nowrap)
DrawMuscle(Brachialis,LowAntHumerus,UlnarTuberosity,nowrap,nowrap)
DrawMuscle(Brachioradialis,LowLatHumerus,LowLatRadius,nowrap,nowrap)
DrawMuscle(TricepsBrachii,UppPostHumerus,UlnarOlecranon,nowrap,nowrap)
DrawMuscle(LongHeadPronatorTeres,MedHumeralEpicondyle,MidLatRadius,nowrap,nowrap)
DrawMuscle(ShortHeadPronatorTeres,UppMedUlna,MidLatRadius,nowrap,nowrap)
DrawMuscle(FlexorCarpiUlnaris,MedHumeralEpicondyle,Pal5MetaCarpal,nowrap,nowrap)
DrawMuscle(FlexorCarpiRadialis,MedHumeralEpicondyle,Pal2MetaCarpal,nowrap,nowrap)
DrawMuscle(FlexorDigitorum,UppMedUlna,Pal3DistalPhalanx,FlexorRetinaculum,nowrap)
```

```
DrawMuscle(ExtensorDigitorum,LatHumeralEpicondyle,Dor3DistalPhalanx,ExtensorRetinaculum,nowrap)

DrawMuscle(MidTrapezius,PostT1,LatClavicle,nowrap,nowrap)
DrawMuscle(LowTrapezius,PostT7,LatClavicle,nowrap,nowrap)
DrawMuscle(PectoralisMajor,MidSternum,UppAntHumerus,nowrap,nowrap)
DrawMuscle(UppLatissimusDorsi,PostT7,UppPostHumerus,nowrap,nowrap)
DrawMuscle(LowLatissimusDorsi,PostSacrum,UppPostHumerus,nowrap,nowrap)

DrawMuscle(Psoas,AntT12,LesserTrochanter,PelvicBrim,nowrap)
DrawMuscle(Iliacus,IliacFossa,LesserTrochanter,PelvicBrim,nowrap)
DrawMuscle(GluteusMedius,IliacCrest,GreaterTrochanter,nowrap,nowrap)
DrawMuscle(RectusFemoris,AntInfIliacSpine,Patella,nowrap,nowrap)
DrawMuscle(Semimembranosus,IschialTuberosity,MedTibialCondyle,nowrap,nowrap)
DrawMuscle(BicepsFemoris,IschialTuberosity,HeadFibula,nowrap,nowrap)
DrawMuscle(AdductorMagnus,IschialTuberosity,MidFemoralShaft,nowrap,nowrap)
DrawMuscle(Gracilis,IschialTuberosity,MedFemoralCondyle,nowrap,nowrap)

DrawMuscle(Vasti,UppFemoralShaft,TibialTubercle,Patella,nowrap)
DrawMuscle(LatHeadGastrocnemius,LatFemoralCondyle,Calcaneous,nowrap,nowrap)
DrawMuscle(MedHeadGastrocnemius,MedFemoralCondyle,Calcaneous,nowrap,nowrap)
DrawMuscle(TibialisAnt,UppLatTibia,MedCuneiform,InfExtensorRetinaculum,nowrap)


{* ============================ *}
{* END OF MODEL                 *}
{* ============================ *}
```