UNCONSTRAINED HUMERAL ELEVATION EXPOSURE IN OCCUPATIONAL SETTINGS

by

TAL AMASAY

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There were two primary goals of this work. The first goal was to investigate humeral and scapular kinematics in a simulated workplace environment. The second goal was to validate a triaxial accelerometer (Virtual Corset) for the collection of humeral elevation exposure data in an occupational setting. To achieve the first goal, healthy subjects were asked to perform constrained and functional humeral elevation motions. Differences were observed in scapular kinematics. In addition, the variability between constrained arm elevation and functional overhead tasks was found to be similar. Therefore, to compare scapular kinematics in an occupational group (dental hygienists) a functional work related task was determined to be more appropriate. The dental hygienists performed teeth instrumentation on simulated patients' with both big and average chest girth in a simulated work environment. Dental hygienist's humeral elevation and scapular upward rotation angles were found to be higher while working on

the big chest girth manikin. These differences may increase dental hygienists susceptibility for musculoskeletal disorders.

To achieve the second goal, an in-vitro comparison of angles measured with the Virtual Corset and an inclinometer was conducted under static conditions. Under dynamic conditions the Virtual Corset was compared to a potentiometer, in a pendulum setting. It was found that the Virtual Corset can accurately reconstruct elevation angles under static conditions, root mean square error less than 1□. Under dynamic conditions, the error size was related to the angular velocity and acceleration, and the radius of rotation. To further investigate the Virtual Corset's ability to measure exposure parameters in-vivo the Virtual Corset was compare to a magnetic tracking device. To do so dental hygienists performed flossing tasks in a simulated work station. It was found that the Virtual Corset can be used to reconstruct elevation angles, with an acceptable angle error, and to identify exposure parameters in occupational settings similar to the one simulated in the present study.

This dissertation includes unpublished co-authored material.

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I would like to dedicate this work to my lovely wife who earned it by keeping up with me and pushing me forward with her tireless efforts trying to take all the loads off me, raising my kids and making my life easier.

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CHAPTER I

INTRODUCTION

SHOULDER RESEARCH BACKGROUND

Shoulder movement has been investigated in many areas including clinical intervention, sports performance, and workplace design. Clinical interventions include, but are not limited to, the effect of rehabilitation [61, 62, 100, 108], and surgery [27, 33, 37, 105]. Within athletes, an area of concentration is with overhead sports such as baseball, golf and swimming [13, 35, 42, 43, 69, 72, 117]. Occupational musculoskeletal disorders have been studied in professions such as mechanics, painters, custodians, office, construction, assembly lines and dental care workers. [14, 19, 21, 24, 32, 57, 70, 75, 76, 89-91, 94, 98, 103, 106].

Proper arm elevation is the result of the interaction between the glenohumeral and scapulothoracic joints. The scapula serves as a stable base for the glenohumeral joint and contributes to arm elevation (scapulohumeral rhythm)[12, 36, 64]. Therefore, abnormal position and/or orientation of these bones may interfere with optimal shoulder coordination. Abnormal scapulothoracic joint motion has been found to be associated with pathologies such as idiopathic loss of shoulder range of motion [87], shoulder instability [60] shoulder impingement [53], frozen shoulder [86] and rotator cuff tears [67, 79].

MUSCULOSKELETAL DISORDERS IN THE WORKPLACE

Shoulder pathologies are included under the broad term of musculoskeletal disorders. Musculoskeletal disorders are defined by the United States Department of Labor as an injury or disorder of the muscles, nerves, tendons, joints, or cartilage when the event or exposure leading to the injury or illness is bending, reaching, twisting, overexertion, or repetition. The outcome may be sprains, strains, tears, soreness and/or pain [8].

A comprehensive review of epidemiological studies examining the association of selected musculoskeletal disorders with exposure to physical factors in the workplace was performed by the National Institute of Occupational Safety and Health (NIOSH) in 1997. In this review three body areas were identified as susceptive for musculoskeletal disorders: the low back, neck and shoulder. Strong evidences were found, which associated musculoskeletal disorders in the workplace with exposure to work related physical factors for the back, neck and shoulder [5]

Bernard et al (1997) found evidence for a causal relation between low back musculoskeletal disorders and occupational exposure to forceful movement, awkward posture, heavy physical work and whole body vibration [5]. Static and dynamic biomechanical models of the lower back have identified five risk factors associated with stress to the lower back including weight lifted, horizontal reach distance, trunk posture, lift frequency and lift dynamics [41].

In the literature, the neck region is divided into neck or neck/shoulder. The logic behind the use of neck/shoulder is related to the fact that the neck and shoulder share muscles such as the trapezius. Evidences for a causal relation between neck and neck/shoulder musculoskeletal disorders and occupational exposure to repetition, force and posture were found [5, 75]. The present study will concentrate on exposure to occupational risk factors and their relation to shoulder musculoskeletal disorders.

Posture and repetition were the two physical work factors identified in the NIOSH review of epidemiological studies that were associated with shoulder musculoskeletal disorders [5]. Activities that associated with the onset of shoulder musculoskeletal disorders may arise from common movements that were performed repeatedly in awkward positions without sufficient recovery time [114]. Trapezius myalgia is a common shoulder disorder that is associated with static position and monotonous stationary position of the neck, shoulder and back. Rotator cuff tendonitis, sub-deltoid bursitis and bicipital tendonitis were also identified as common musculoskeletal disorders that are associated with repetitive shoulder motion mainly in abduction and flexion and overhead arm postures [56].

The United States Department of Labor has reported that in 2005 there were a total of 1.2 million injuries and illnesses requiring days away from work in the private industry. Out of those, 30% were due to musculoskeletal injuries. The injury mechanism that resulted in the longest absences from work was repetitive motion. The injuries that resulted in the longest absences from work were in the shoulder [8]. In an epidemiologic study of work related upper extremity musculoskeletal disorders, conducted in France's Pay de la Loire region, it was found that more than 50% of the participating workers in the study suffered from non-specific musculoskeletal symptoms. The most common disorder identified was rotator cuff syndrome. Moreover, the prevalence of upper extremity musculoskeletal disorders increased with age [83].

CONSTRAINED AND FUNCTIONAL SHOULDER MOVEMENTS

Many studies have been performed to evaluate scapulothoracic joint kinematics and its role in shoulder movement in different populations. Constrained protocols are commonly used in measurement of shoulder kinematics. Four main methods have been used to constrain shoulder movement: 1) measuring scapulothoracic joint position at different static humeral elevation angles [36, 51, 79], 2) constraining shoulder movement to a specific plane of motion, typically the frontal, sagittal and scapular planes [17, 62, 77], 3) restricting joint (other than the shoulder) or segment motion by instructing the subject to hold the position of a specific segments during motion, such as extending their elbow [64, 67], and 4) restricting motion using a specially designed apparatus or splint [40, 66, 108] or any combination of the above options. Few studies have measured scapulothoracic joint kinematics in unconstrained (functional) scenarios, such as during wheelchair propulsion and transfer activities [23, 73, 84], and during activities of daily living, such as reaching, perineal care, hair combing, and eating [45, 46, 55, 105].

To the best of our knowledge there are only two published studies[55, 105] that have compared scapular kinematics between constrained and functional humeral movements. However these studies made the comparison only at the end range of motion of a hair combing task, with no information provided on the scapular path through the whole range of motion in comparison to the constrained humeral elevation. Furthermore, to evaluate functional lower extremity motion, gait analysis is commonly used. However, there is no one agreed-upon functional testing protocol to evaluate shoulder kinematics in healthy and non-healthy subjects. The most commonly used testing protocol for shoulder kinematics involves constrained scapular plane elevation. Based on this literature review, the present study will compare scapular kinematics and variability between constrained and functional testing at the same humeral elevation and plane of elevation.

EXPOSURE IN THE WORK PLACE

One of the main issues in occupational studies focusing on musculoskeletal disorders of the upper extremity is to quantify workers' exposures to risk factors during a work day. It has been shown that workers are more susceptible to shoulder injury when exposure to arm elevation higher than 60° [75] or 90° during the work day [81, 94, 96]. Three main physical risk factors have been identified: force (intensity and duration), repetition, and posture (awkward and constrained) [5].

Assessment of occupational exposures in field settings is very challenging. Three methods are commonly used to determine exposure: (1) self reporting, questionnaire and interview, (2) observational methods and (3) direct measurement [15, 44]. The first two methods are subjective whereas, direct measurement is objective and provides precise measurements; hence, it is usually preferred. However, high cost of equipment, trained technicians and data analysis, duration of setting and calibration, unsafe work environments for the equipment and staff, constrained recording area, and limited recording time limits the utility of some of the high end systems in the workplace.

To overcome these disadvantages, low cost, whole day ambulatory recordings, body-mounted transducers combined with data loggers are used. To estimate elevation angle exposure in the upper extremity, goniometers [32, 76] and inclinometers have been used. An inclinometer is a transducer that measures an elevation/inclination angle relative to gravity. Different types of transducers were developed and used to measure elevation angle exposure such as the abduflex [21, 97] consisting of mercury microswitches, Intometer [91] consisting of pressure transducers and distilled water, Physiometer [103] consisting of electrolytic liquid level sensors, and accelerometers [6, 19, 30, 31, 59, 70], which are the most common.

However, these devices have limitations due to their construction. Most are clumsy mainly instrumented with cable connections between the transducers and data loggers. Some of the devices are complicated to mount and align with the coordinate system of the body segment, and/or the transducer's attachment to be affixed to the subject. Moreover, others suffer from limited measuring range and low data collection sampling rate. The accelerometer's main problems are sensitivity to linear acceleration and detection of only two axes of rotation. Any linear acceleration introduced in addition to gravity will bias the calculated elevation angles. Also, rotation about the axis parallel to gravity will not be detected by the accelerometers and may bias the calculated elevation angles. Based on this literature review, this study will validate a tri-axial accelerometer (Virtual Corset) for the prediction of elevation angles under static and dynamic conditions.

DENTAL HYGIENISTS

Studies have shown that dental hygienists suffer from musculoskeletal disorders in the neck (37% - 72%) [48, 71], upper extremity (11% - 68%) [1, 48, 71, 110, 111] and back (15% - 65%) [48, 82] and the prevalence of these musculoskeletal disorders increases with years of occupation [1, 48, 71, 82]. Several of these upper extremity pathologies are carpal tunnel syndrome, elbow tendinitis, shoulder impingement and rotator cuff tears. One of the main problems in evaluating the occurrence and prevalence of musculoskeletal disorder in this population is related to the definition of the affected body area. For example, Lidfors et al found that 81% of the dental hygienists in their study reported suffering from upper extremity disorders. However, their definition for upper extremity includes the fingers, hand, wrist, elbow, shoulder and neck [47]. Akesson et al. and Morse et al. have found that the prevalence of shoulder musculoskeletal disorders was high, 35.1% - 68% [1, 71]. Werner et al. found that 13% of the dental hygienist in his study suffer from shoulder tendinitis [111]. Liss et al. found that dental hygienist are 2.8 times more likely to report shoulder problems than dental assistants, during a 12-month period [48]. Nonetheless, there has not been a great deal of research performed on this group, with most of the research being based on questionnaires and physician evaluation.

To the best of our knowledge, there is only one published study which tried to measure dental hygienist kinematics and it was performed in the work place using a video recorder [57]. Markling et al (2005) found that dental hygienists' left arms were abducted 45% of the time while the right arms were abducted 34% of the time. Moreover, shoulders were abducted over 30° of elevation more than 50% of the time, and this posture was mainly static [57]. However, this study didn't use any marker settings and was a 2D estimation of back and neck flexion, and humeral abduction. Consequently, the use of a video camera may have introduced projection errors related to the camera and the dental hygienist positions. Furthermore, there are no reports in the literature on 3D humeral and scapular kinematics of dental hygienists. There is one study on dentists which have measured 3D shoulder kinematics in the work place, without using markers placement setup [25].

During a work day, dental hygienists work with a wide population, kids to elderly and lean body type to obese body type. This may introduce various difficulties and constraints to the dental hygienist. Since the mid-seventies, the prevalence of overweight and obesity has increased sharply for both adults and children. Data from the Centers for Disease Control and Prevention (CDC) show that among adults aged 20–74 years the prevalence of obesity increased from 15.0% in the late seventies to 32.9% in 2003–2004. It also showed an increase in overweight among children and teens. In 2006, only four states had a prevalence of obesity less than 20% for the whole population. The increase in population obesity may introduce a more pronounced problem for the dental hygienist as a result of inappropriate dental equipment to accommodate to the patients' larger body size [11].

Since there are no data on dental hygienists' scapular kinematics and there is only one study [57] which quantified dental hygienists' shoulder's exposure, this present study will measure dental hygienists' scapular kinematics in a simulated workplace environment using a magnetic tracking device. It will also validate the Virtual Corset's ability to quantify shoulder elevation exposure.

SPECIFIC AIMS

The purpose of the project is to quantify scapular and humeral kinematics of dental hygienists in a simulated workplace environment. There are three objectives to this project. The first objective is to investigate and compare scapular kinematics under constrained and unconstrained shoulder movement. The second objective is to validate the use of a tri-axial accelerometer (Virtual Corset) to detect and predict humeral elevation angles under static and dynamic conditions. The third objective is two-fold. The first goal is to validate the Virtual Corset's ability to detect differences of humeral exposure in a simulated dental hygienist work environment. The second goal is to quantify scapular kinematics among dental hygienist in a simulated work environment using the Polhemus magnetic tracking system.

The rationale for the proposed research is to identify scapular patterns in dental hygienists during simulated work tasks, which could provide insight about their susceptibility to injury. In addition, it is a validation of a device's (Virtual Corset) ability to identify humeral elevation in a simulated work place, which eventually could identify risk factors during a work day. This could lead to investigating future ergonomic solutions for this population.

We plan to accomplish the objectives of this proposal by pursuing the following specific aims:

Specific Aim 1: Determine scapular kinematic differences and variability between constrained and functional shoulder movement in healthy subjects. This study was co-authored with Dr. Karduna. To date, scapular kinematics has been study using mainly constrained protocols. Our goal is to measure differences and variability in scapular kinematics between constrained and functional shoulder movement, at the same humeral elevation and plane of elevation, which will help us to decide the suitability of the constrained or functional models for our study.

Specific Aim 2: Determine the validity of the Virtual Corset to predict elevation angles in controlled static and dynamic conditions, and our ability to predict the errors. This study was co-authored with Dr. Karduna, Dr. Laurel Kincl and Keely Zodrow. Data from the literature have demonstrated that accelerometers can be used to calculate inclination angles in static or quasi-static conditions. Our goal is to validate the Virtual Corset's accuracy in predicting elevation angles under static and dynamic conditions. Introducing linear acceleration besides gravity will increase the errors. If a prediction model can be established to predict the errors as a function of the radius, angular velocity and acceleration, and elevation angle, then the magnitude of the error and the validity of the Virtual Corset use in different occupational settings can be predicted.

Specific Aim 3: Compare the effect of controlled in-vivo measurements on the calculated elevation angle relative to a 3D magnetic tracking system in Dental Hygienists. This study was co-authored with Dr. Karduna and Michael Latteri. We want to validate our lab-based study of the Virtual Corset in-vivo. A direct comparison between the Virtual Corset and the Magnetic tracking device will help evaluate the

Virtual Corset's accuracy and ability to identify differences in shoulder elevation in the presence of skin and muscle motion artifact during 3D shoulder motion. This would increase the capacity for objective measures in the workplace to evaluate postures.

Specific Aim 4: Compare the effects of patient's body type (average or obese) on humeral and scapular kinematics of dental hygienists during cleaning work. This study was co-authored with Dr. Karduna. As a result of ergonomic constraints in dental hygienist's workplace, we hypothesis that work with obese patients relative to average patients will result in higher humeral elevation angles on both arms and higher scapular upward rotations.

BRIDGE

Based on the literature review it is not clear which data collection method is preferred to evaluate and investigate scapular behavior in occupational settings. The first research question for this study was: What are the differences in scapular kinematics between constrained and functional shoulder movements in healthy population? To answer this question 25 healthy adults performed two types of tasks constrained arm elevation and functional tasks. Chapter II describes the differences in scapular kinematics between six different functional tasks and constrained arm elevation at different planes in corresponding humeral plane of elevation and elevation angles.

CHAPTER II

SCAPULAR KINEMATICS IN CONSTRAINED AND UNCONSTRAINED UPPER EXTREMITY MOVEMENTS

In the following study all data collection was performed by me. Dr. Karduna assisted with statistical analysis, interpretation of the results, and manuscript editing.

INTRODUCTION

Shoulder movements have been investigated with respect to many applications, including sports performance, workplace design, and clinical intervention. Within this area of research it is well established that proper arm elevation is the result of the interaction between the glenohumeral and scapulothoracic joints. The scapula serves as a stable base for the glenohumeral joint and contributes to arm elevation (scapulohumeral rhythm). Therefore, altered scapular position and/or orientation may interfere with optimal shoulder coordination. Abnormal scapulothoracic joint motion has been found to be associated with pathologies such as unstable shoulder[60], frozen shoulder[85, 86], and shoulder impingement [53].

Many studies have been performed to evaluate scapulothoracic joint kinematics and its role in shoulder movement in different populations. Constrained protocols are commonly used in the measurement of shoulder kinematics. Four main methods were identified in the literature that have been used to constrain shoulder movement: 1) measuring scapulothoracic joint position at different static humeral elevation angles [36, 51, 79], 2) constraining shoulder movement to a specific plane of motion, typically the frontal, sagittal or scapular planes [17, 62, 77], 3) restricting joint (other than the shoulder) or segment motion by instructing the subject to hold the position of a specific segments during motion, such as extending their elbow [64, 67], and 4) restricting motion using a specially designed apparatus or splint [40, 66, 108] or any combination of the above options. However, few studies have measured scapulothoracic joint kinematics in unconstrained (functional) scenarios, such as during wheelchair propulsion and transfer activities [23, 73, 84], and during activities of daily living, such as reaching, perineal care, hair combing, and eating [45, 46, 55, 105].

To the best of our knowledge there is only one published study[55] which have compared scapular kinematics between constrained and functional humeral movements. However this study made the comparison only at the end range of motion of a hair combing task, which did not elaborate on the scapular path through the whole range of motion in comparison to constrained humeral elevation. To evaluate functional lower extremity motion, gait analysis is commonly used. However, there is no one agreed-upon functional testing protocol to evaluate shoulder kinematics in healthy and non-healthy subjects. The most commonly used testing protocol for shoulder kinematics involves constrained scapular plane elevation.

The purpose of the present study is to investigate and compare scapular kinematic behavior under constrained and functional shoulder movements. In the present study, shoulder movement was constrained using methods two and three, that is constraining shoulder movement to a specific plane and restricting joint motion by instructing the subject to hold the position. This led us to consider the following research questions: 1) What are the differences in scapula orientation between constrained and unconstrained tasks at a specific humeral orientation based on humeral plane of elevation and humeral elevation? 2) Is the between-subject variability smaller during constrained scapular plane arm elevation than overhead functional tasks?

METHODS

Subjects

Twenty five healthy subjects (12 males, 13 females) participated in this study with a mean age of 25.8 (6.4) yrs, height of 1.74 (0.08) m, and weight of 70.1 (21.9) kg). The University of Oregon Institutional Review Board approved this study and consent was obtained prior to data collection. All participants were right handed, and had no history of shoulder surgery. The subjects did not suffer from any injury that required rehabilitation within the previous two years. They had no limitation in humeral elevation range of motion, and did not suffer from any known neurological problems. They were instructed not to perform heavy upper body exercises 24 hours prior to testing.

Instrumentation

Three dimensional kinematic data from the scapula, humerus and thorax were collected via the Polhemus Liberty magnetic tracking system (Colchester, VT), which consisted of an electronics unit, a transmitter, three sensors and one digitizer. This system was interfaced with the MotionMonitor software program (Innovative sports Training, Chicago, IL). Data were collected at a rate of 120 Hz per sensor. The transmitter emitted an electromagnetic field that was detected by the digitizer and the sensors. The system's electronic unit determined the relative orientation and position of the sensors in space. Data analysis and interpolation were executed using LabView software (National Instruments, Austin, TX).

Set-up and Digitization

Three sensors were placed on each subject. A thoracic sensor was attached, using double-sided adhesive tape, to the manubrium just below the jugular notch, then secured in place with adhesive tape. A scapular tracker, previously validated in our lab, was used to quantify scapular kinematics [39]. Plastic screws secured a sensor to the scapular tracker jig. The jig was attached atop the spine of the scapula and acromial process, using adhesive Velcro strips. The humeral sensor was placed on the humerus over the deltoid tuberosity using a customized molded cuff attached by Velcro strips. This way of securing the sensors to the different segments is used in this research lab and its reliability was tested [102]. A global coordinate system was established by mounting the transmitter on a rigid plastic base. The transmitter was located behind the tested arm at the humeral sensor height, at a horizontal distance of 30 cm from the trunk. A foot alignment device was use to determine each participant's preferred feet position during digitization (Figure 2.1). This device was used later to reposition the participants at their initial preferred position, after each rest period, to standardize the foot position during each trial.

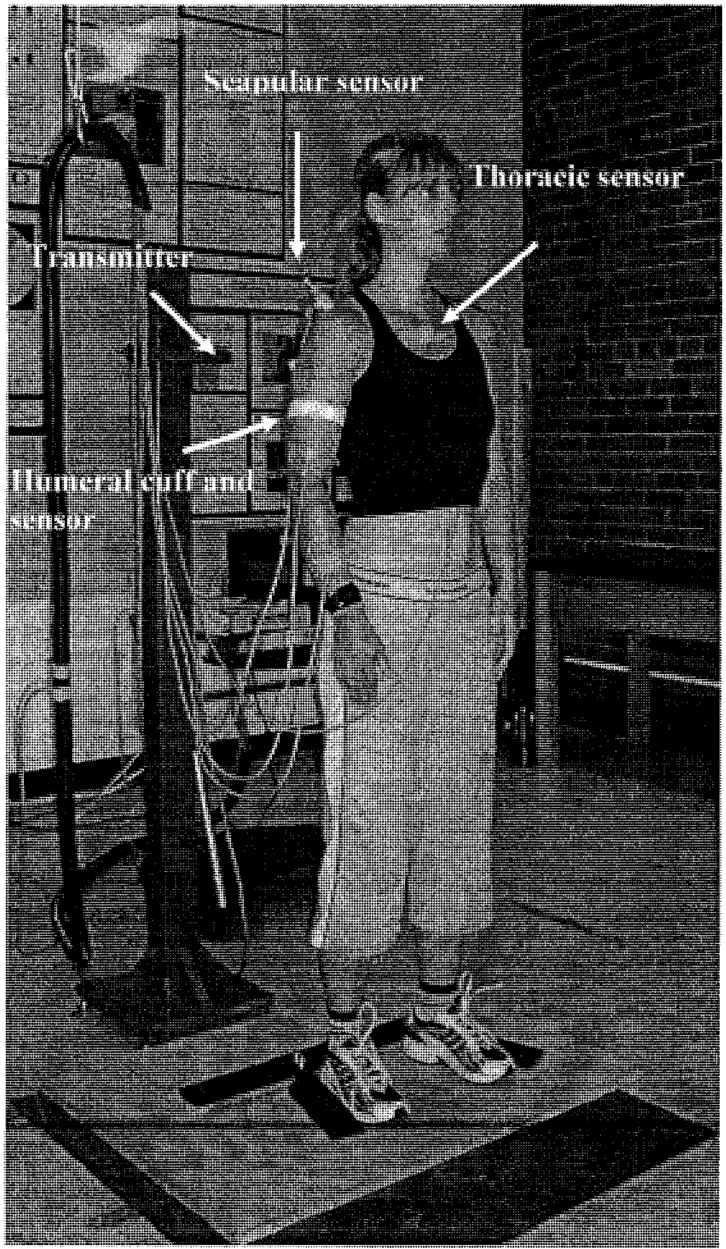


Figure 2.1. Study setup and sensors placement. Note that the forearm sensor is not related to the present study.

Anthropometrical measurements were taken from each participant using a measuring tape. Upper extremity length was measured from the anterior aspect of the acromial process to the tip of the middle finger with the arm extended at the sides and the participant in a seated position [46]. In the next three measurements the participants were standing in their natural position. Shoulder height was measured from the anterior aspect of the acromial process to the ground. Body height was measured from the head apex to the ground. Shoulder width was measured from the lateral aspect of the left acromion process to the lateral aspect of the right acromial process.

Throughout digitization and data collection trials, participants were in their natural standing position. During the digitization trial, anatomical landmarks were digitized for the thorax (T8, xiphoid process, C7 and jugular notch), scapula (root of spine of the scapula, acromial angle and inferior angle) and humerus (medial and lateral epicondyles and ulnar styloid process). The arbitrary axes defined by the magnetic tracking system were converted to anatomically appropriate embedded axes derived from the digitized bony landmarks, based on the ISB recommendation for the upper extremity [116]. All landmarks were surface points and, therefore, could be located directly, except for the center of the humeral head. The center of the humeral head was defined as the point on the humerus that moved the least with respect to the scapula while moving the humerus through short arcs (< 45 degrees) of mid-range glenohumeral motion and was calculated using a least-squares algorithm [104]. After the digitization process, the raw data from the sensors were converted into anatomically defined rotations that could be displayed in real time using the MotionMonitor software. Standard matrix transformation methods were used to determine the rotational matrix of the humerus and scapula with respect to the thorax. For the humerus, the ISB second recommendation was used, taking the ulnar styloid process as the third point for the plane, with the elbow in 90° of flexion [116]. Humeral rotations were represented using a standard Euler angle sequence (Y X' Y") in which the first rotation defined the plane of elevation, the second rotation described the amount of elevation and the last rotation represented the amount of internal/external rotation. Scapular rotations were represented using an Euler angle sequence (Y Z' X") of external/internal rotation, upward/downward rotation, and anterior/posterior tilting.

Experimental Procedure

Participants started the experiment with a standardized warm-up procedure, which included Codman's pendulums and stretches for the rotator cuff muscles. To perform Codman's pendulum the subjects bent forward while supporting their body with the non-dominant arm on a table, and holding a 1.1 kg weight in their dominant arm with their arm stretched down. Each subject performed a set of 15 repetitions of arm circles, clockwise and counterclockwise, followed by a set of 15 repetitions of a back and forth movement in the sagittal plane. The stretches consisted of holding a static external and then internal rotation position while the shoulder was abducted in the frontal plane to approximately 90°, for two sets of 15 s each [93]. Data collection followed, first with the functional task trials and then the constrained trials. Pilot data collection revealed that subjects had altered the way they reached to the different functional targets when the constrained tasks were introduced first. All testing were completed in a single session and performed on the dominant upper extremity.

The functional testing protocol consisted of six tasks. These tasks represented activities of daily living, with an attempt to cover a wide range of different humeral planes of elevation and elevations. Several of the tasks presented by Lin et al. [46] were modified based on pilot data, because their subjects were in a seated position where as in this study the subjects were in standing position. Participants practiced each reaching task as much as they needed until they felt comfortable to perform it. They were instructed not to move their feet during all tasks. For the first five tasks targets' height locations were measured above or below shoulder (superior aspect of the acromial process) height. The horizontal distance for the targets located in the frontal plane was measured from the acromion process lateral aspect of the dominant arm. The horizontal distance for the targets located in the sagittal plane was measured from the heels. Task descriptions and locations were as followed: (1) Reaching to a seat belt (Belt), in the frontal plane at a horizontal distance of 75% of arm length at shoulder height; (2) Reaching to a shelf (Shelf), in the sagittal plane at a horizontal distance of 80% of arm length and height of 50% of arm length above shoulder height; (3) Reaching out (Reach Out), in the sagittal plane at a horizontal distance of 120% of arm length and height of 66% of arm length below shoulder height; (4) Reaching to an object on the right side (Object Right), in the frontal plane at a horizontal distance of 66% of arm length and height of 66% of arm length below shoulder height; (5) Reaching to an object on the left side (Object Left), in the frontal plane, at a horizontal distance of 50% of arm length and height of 66% of arm length below shoulder height. (6) Reaching to an imaginary point above their head (Overhead). For the first five tasks the instructions were to reach to the target, which was a small plastic object (negligible weight) on a shelf, and bring it back to the side of the body. For the sixth task they were instructed to reach as high as possible (Figure 2.2A-F). All target locations were normalized based on the participant's height, shoulder height and width, and dominant arm length, and trial order was randomized.

After performing these functional tasks, each participant performed constrained arm elevations in various planes, ranging from 0° (frontal plane) to 120°, where 90° represented the sagittal plane. This range was divided into six different trials of 20° intervals, each starting at a different plane of elevation angle (0°, 20°, 40°, 60°, 80° and 100°). For each trial, subjects were instructed to elevate their arm along the path of a series of seven equally distributed vertical lines secured to a mobile 0.6m X 1.9m board. These lines were spaced at approximately 3° increments of plane of elevation. Participants were instructed to keep their elbow extended and thumb pointing up and to elevate their arm as high as possible, restricting trunk and feet movements (Figure 2.2G).

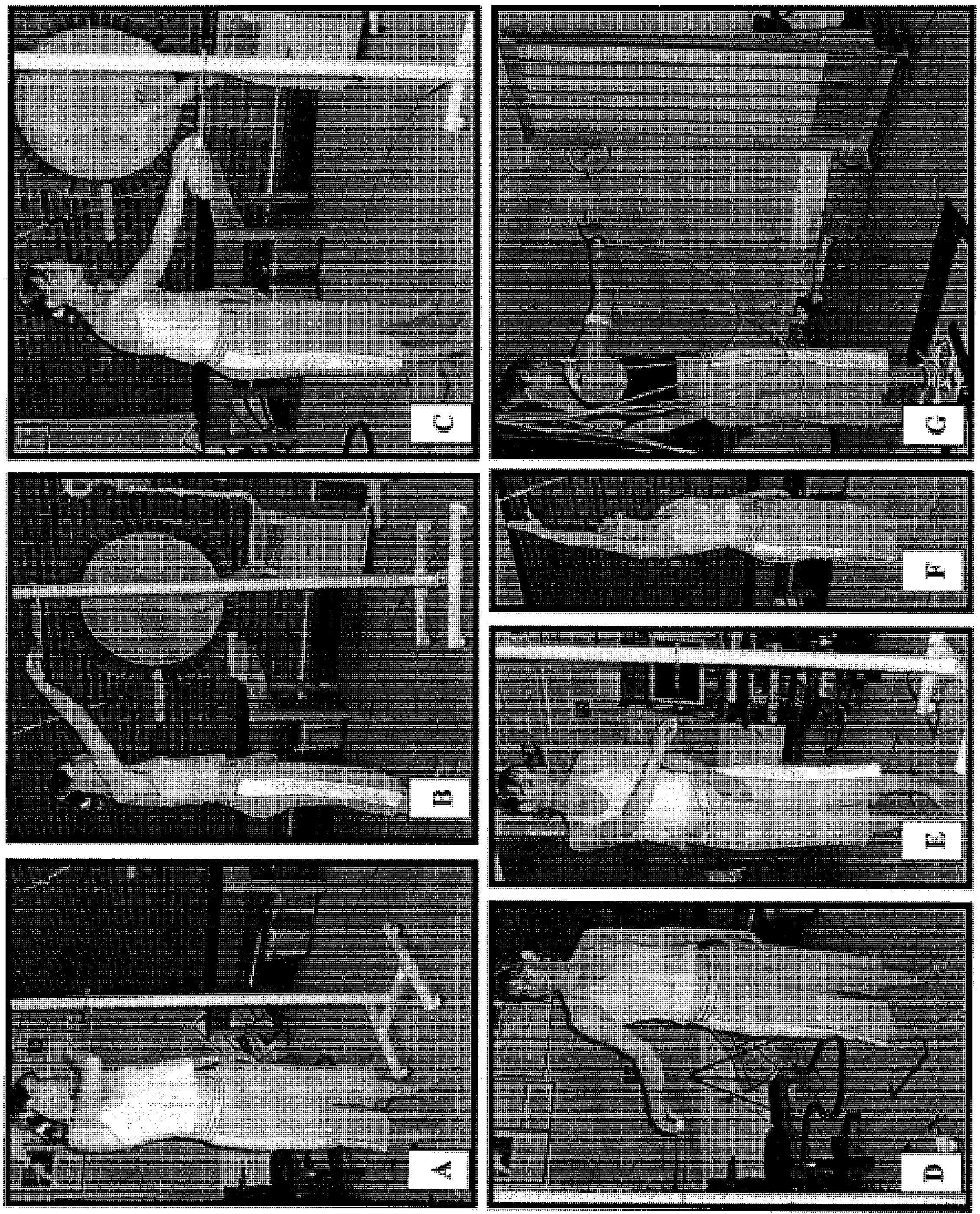


Figure 2.2. Photographs of the motions performed by subjects: A) Belt, B) Shelf, C) Reach Out, D) Object Right, E) Object Left, F) Overhead G) Constrained trial at 60° - 80° range.

A metronome set at 84 beeps per minute was used to control the arm's average angular velocity to approximately 40°/s. Participants elevated and lowered their arms to the count of four beeps for each direction. Participants practiced each constrained trial as much as they needed until they felt comfortable to perform it. During all trials the researcher closely observed the participants' arm motion and trunk position and verbally instructed them if needed to keep the desired arm and trunk positions. After each trial the participants rested for 3 minutes. Trial order was randomized. After six trials, which consisted of a total of 42 constrained arm elevations, the functional task data were plotted against the constrained data comparing humeral plane of elevation and humeral elevation. Data were visually inspected to ensure that most of the points of the functional tasks were encompassed in the area of the constrained trials. If a gap of 10° or higher in plane of elevation was identified within the constrained data, the participants had to repeat another constrained trial, at the same area, which increased subject's total constrained arm elevation to 49 trials.

Data Analysis (Reduction)

Before any analysis was performed, all data were trimmed below 20° of humeral elevation angles (to avoid Gimble Lock about the first humeral rotation) and above 120° of humeral elevation angles to minimize skin slippage error of the scapula tracker [39]. A correction equation, previously used in our lab [39] was used to correct scapular upward rotation for the constrained and functional data which further reduced skin movement artifact. This method reported a RMS angle error, related to skin slip, of 6.2° and smaller for scapular rotations. The constrained data were matched to the functional data based on humeral elevation and plane of elevation angles for each participant using a customized LabView program. For each trial the constrained humeral elevation angles were linearly interpolated to increments of 0.1 degrees. This algorithm was used to interpolate all the corresponding humeral and scapular angles. Next, for each functional data point all the matched corresponding constrained humeral elevation angles were pulled out. At each matched humeral elevation angle data were searched for the two closest constrained humeral planes of elevation angles that encompass the corresponding functional humeral plane of elevation angle. These constrained planes of elevation angles were linearly interpolated to match their corresponding functional tasks plane of elevation angles. This algorithm was used to interpolate all the corresponding humeral external/internal rotation and scapular angles. In this way, for every data point of the functional protocol, there was a corresponding interpolated constrained data point, at the same humeral elevation and plane of elevation angles (Figure 2.3).

Separate two-way ANOVA's with repeated measures were conducted to examine the effect of constrained and unconstrained shoulder movement (condition) on scapular angles (depended variable) at different humeral elevation angles (position), for each functional task. The position ranged from 30° to 120°, in 30° increments of humeral elevation angles depended of the functional task range of motion. If significant interactions were found between the condition and the position, a post hoc Bonferroni-Holm procedure was used [113]. For each task, scapular angles differences between the functional data and the interpolated constrained data were calculated, averaged between participants and plotted. These graphs were searched for patterns which could explain the differences in scapular orientations as a function of humeral elevation angles.

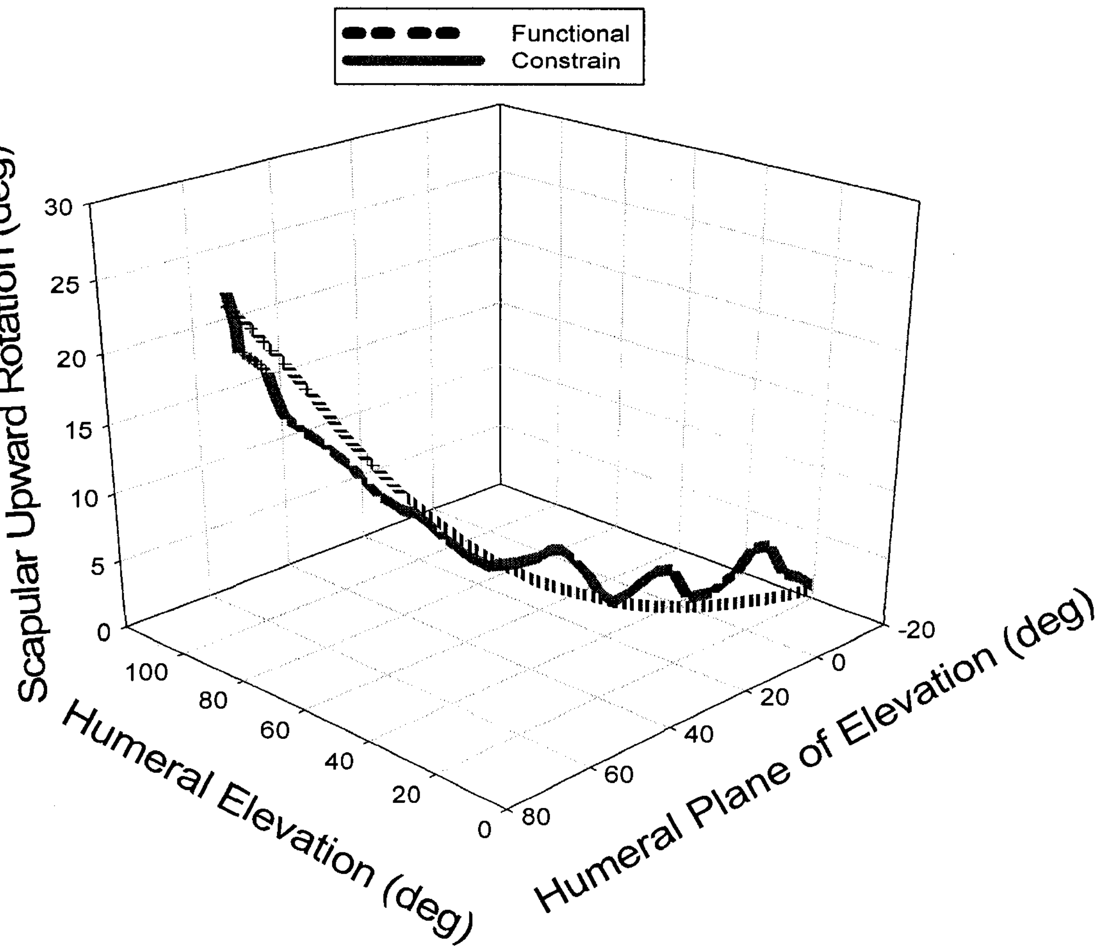


Figure 2.3. Representative 3D representation of the functional shelf task and its corresponding interpolated constrained data.

For each subject the raw constrained data were searched to identify the specific trial that was performed in the scapular plane. The scapular plane was identified as the trial closest to 35° of plane of elevation at 90° of humeral elevation (practically, this resulted in a mean of 35° ± 0.8°). Out of the six functional tasks Shelf and Overhead tasks were the only ones which involved overhead motion. For each of the overhead functional tasks and the constrained trial, the average and standard deviation of scapular upward rotation angles were plotted at specific humeral elevation angles. Variability was compared between the functional tasks and the constrained humeral elevation by using the coefficient of multiple correlation (CMC) comparing the estimated variance in each of the scapular angles. The CMC value reflects the variation between groups of waveforms as a percentage of the total variation of this group of waveforms. The CMC was used to evaluate the similarity between waveforms in gait analysis [38, 92] shoulder [54] and scapular motion [99]. When the waveforms are similar, CMC value is close to 1; if the waveforms are dissimilar, CMC value is close to 0. This expression yielded a measure of repeatability of waveforms [74].

RESULTS

The first goal of this study was to compare scapular orientation between constrained and functional shoulder motion. The statistical analysis revealed significant condition by position interaction effect on all scapular orientation ($p < 0.05$). A post hoc Bonferroni-Holm test found in most of the cases significant differences in scapular angles between the conditions for all the tasks (Table 2.1). For scapular external rotations maximum average angle difference of 6.4° was found in the Reach Out task at 60° of humeral elevation. No significant differences were found in the Belt task at humeral elevation angles of 30° and 60° and in the Overhead task at a humeral elevation angle of

Table 2.1. Mean and SD in scapular angles between Functional (Ucon) and constrained (Con) shoulder motion at specific humeral elevation angles during specific tasks

		Scapular Rotations					
		External Rotation (deg)		Upward Rotation (deg)		Posterior Tilt (deg)	
Tasks	Humeral Elevation (deg)	Ucon	Con	Ucon	Con	Ucon	Con
Belt	30	32.2 (7.0)	33.3 (7.5)	1.0 (4.9)*	-6.4 (4.9)	-9.5 (7.7)*	-11.1 (8.2)
	60	38.8 (7.4)	39.7 (6.9)	12.9 (7.9)*	5.5 (6.8)	-8.8 (7.7)	-10.7 (6.9)
Shelf	30	27.2 (7.3)*	29.5 (8.4)	0.4 (4.7)*	-5.9 (4,7)	-9.5 (7.5)	-10.4 (8.3)
	60	29.2 (7.8)*	33.7 (8.8)	10.7 (5.1)*	2.5 (5.7)	-6.0 (8.1)*	-8.3 (8.4)
	90	34.5 (8.6)*	37.2 (10.1)	24.4 (5.8)*	16.6 (6.8)	-4.4 (7.8)	-6.6 (8.7)
Reach Out	30	35.5 (6.9)*	30.6 (7.9)	-10.6 (5.7)*	-5.2 (5.1)	-12.3 (6.7)*	-10.7 (8.9)
	60	41.9 (8.0)*	35.5 (11.0)	-3.2 (10.3)*	6.0 (9.0)	-10.9 (5.1)	-10.2 (7.7)
Object Right	30	27.1 (7.4)*	22.2 (7.7)	-8.6 (8.0)*	-3.0 (8.4)	-11.5 (6.2)*	-9.2 (5.8)
Object Left	30	36.1 (6.5)*	33.7 (6.7)	-5.8 (8.2)	-3.7 (7.8)	-13.8 (4.9)*	-12.1 (4.2)
Overhead	30	25.4 (9.9)*	27.9 (10.2)	1.6 (3.9)*	-4.9 (4.6)	-8.2 (7.8)	-8.1 (7.4)
	60	25.7 (10.7)*	31.6 (10.4)	13.6 (4.5)*	3.9 (5.4)	-4.4 (8.6)*	-6.4 (8.4)
	90	27.4 (11.2)*	32.9 (11.8)	26.9 (4.5)*	17.8 (6.2)	-1.6 (8.9)*	-4.8 (8.5)
	120	31.4 (13.4)	29.2 (12.6)	39.8 (4.2)*	34.4 (4.0)	-1.3 (10.3)	-2.4 (10.0)

- Statistically significant value at $p<.05$

120°. For scapular upwards rotations maximum average angle difference of 9.7° was found in the Overhead task at 60° of humeral elevation. No significant difference was found in the Object Left task at 30° of humeral elevation. For scapular posterior tilting maximum average angle difference of 3.2° was found in the Overhead task at 90° of humeral elevation.

To identify patterns of the differences between the constrained and functional scapular data, all data were averaged based on humeral elevation angles (Figure 2.4). Positive differences in scapular angles represent functional angles that were larger than constrained angles. Evaluation of these data revealed that the Belt, Shelf and Overhead tasks have the same general patterns within each of the three scapular rotations. Scapular angle differences during the Reach Out, Object Right and Object Left tasks were found to have the same general patterns, however, opposite of the patterns seen in the Belt, Shelf and Overhead tasks.

The second goal of the present study was to compare between subject variability for scapular upward rotation in the Overhead and Shelf functional tasks and constrained arm elevation in the scapular plane. The shape and the standard deviation of the three different tasks were similar (Figure 2.5). The CMC values showed that the scapular orientation variability between the overhead functional tasks and the constrained arm elevation in the scapular plane were similar (Table 2.2).

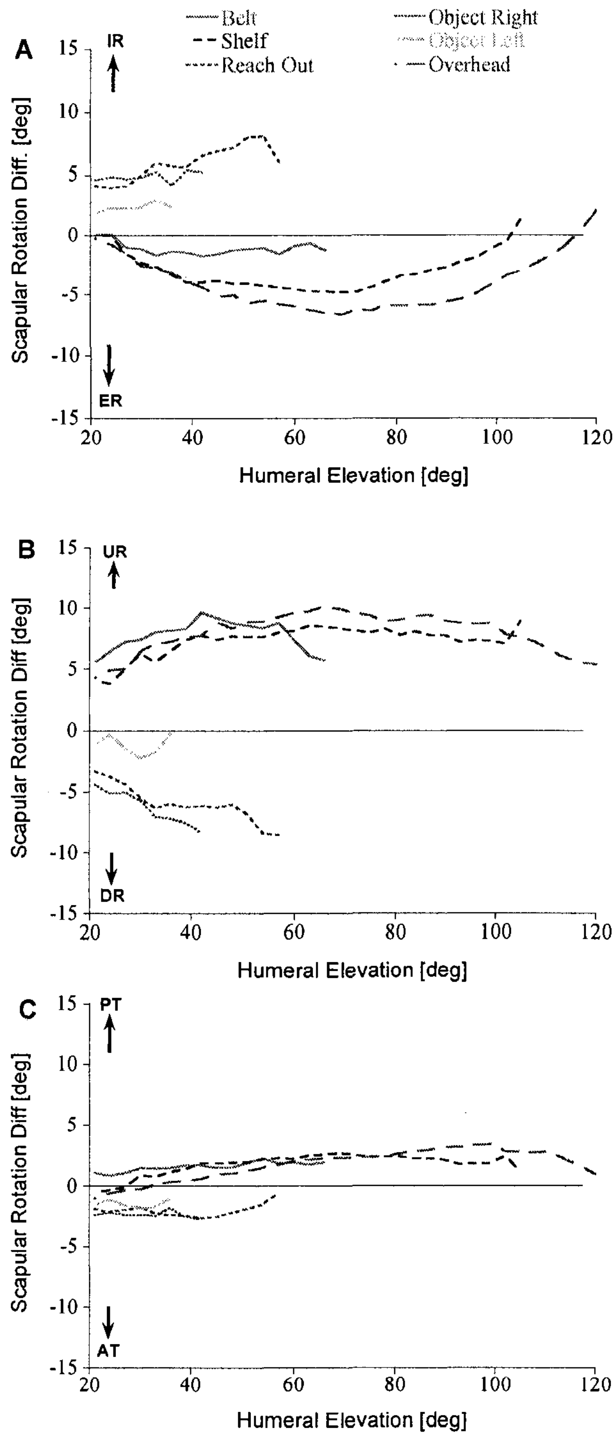


Figure 2.4. Mean differences between constrained and functional tasks scapular angles as a function of humeral elevation angle for (A) scapular internal/external rotation (IR/ER), (B) scapular upward/downward rotation (UR/DR) and (C) scapular posterior/anterior tilt (PT/AT).

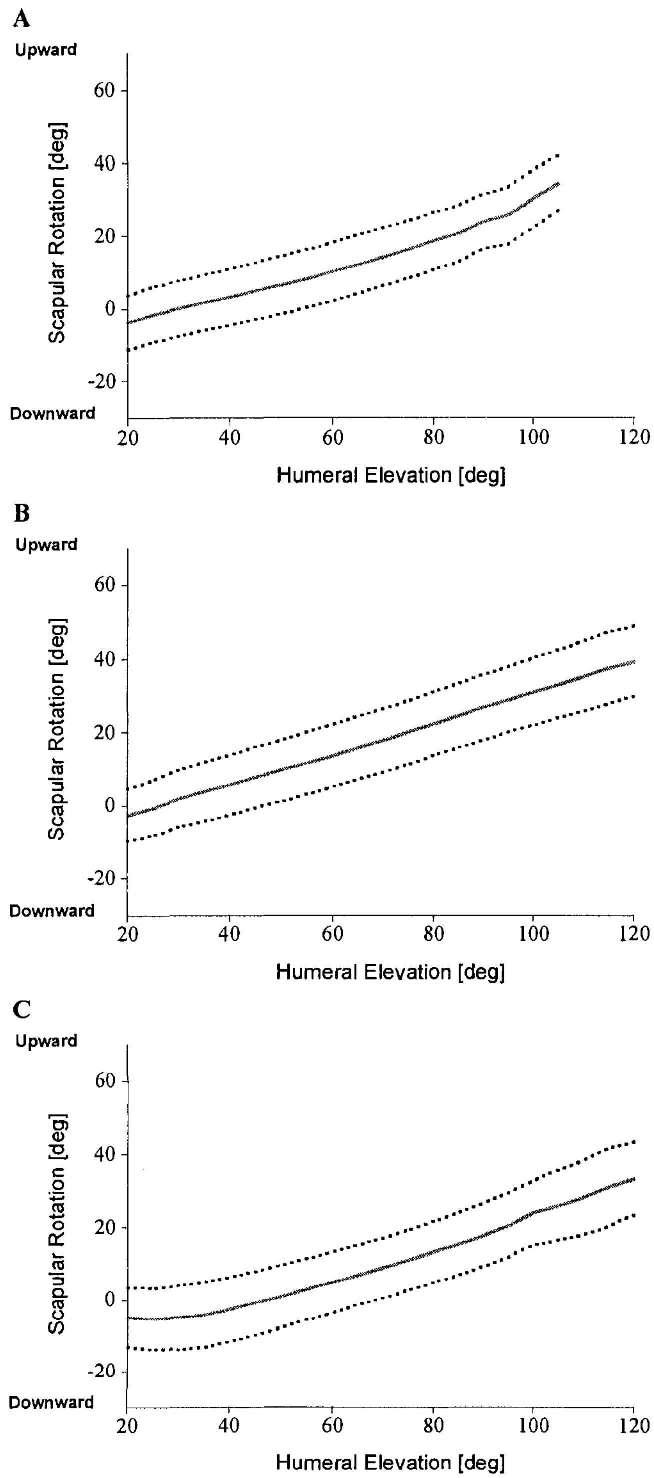


Figure 2.5. Mean and SD of scapular upward rotation as a function of humeral elevation in: (A) Shelf task, (B) Overhead task and (C) constrained scapular plane of elevation

Table 2.2. Between-subject scapular orientation coefficient of multiple correlation (CMC) between Overhead and Shelf functional tasks and constrained shoulder movement at scapular plane (constrained).

	Internal Rotation	Upward Rotation	Posterior Tilt
	CMC	CMC	CMC
Constrained	0.11	0.69	0.33
Shelf	0.20	0.66	0.38
Overhead	0.18	0.82	0.57

DISCUSSION

The present study compared scapular behavior under two conditions: constrained and functional shoulder motion. Six functional tasks were compared covering a wide combination of humeral elevation and plane of elevation, with constrained arm elevation covering a wide range of planes of elevation. The comparison of scapular motion between the two conditions was performed at the same humeral elevation and plane of elevation angles. As was mentioned previously a large number of studies have been performed on constrained shoulder motion and few have been performed on functional shoulder movement, however, none of these studies compared the two conditions at a wide range of motion.

The two-way ANOVA's with repeated measures, which was followed by post hoc procedure found significant difference of the means in most of the conditions. Scapular upward rotation had the highest mean angle differences in all the tasks. Scapular posterior tilt was the angle which had fewer significant differences; this may be related to its relative small range of motion. However, differences between functional and constrained data did not take into account the magnitude of the angle difference relative to the average range of motion for each scapular rotation in each task, ratio. The highest ratio value of 1.6 (160%) was found in the scapular upward rotation of Object Right task. The Reach Out task had the second highest ratio value of 1.2 (120%) in the scapular upward rotation, however the Overhead, Shelf, Belt and Object Left tasks had a lower ratio values in general. These findings suggested that Object Right and Reach Out tasks had higher variability in the way the subjects executed the tasks. In these tasks the mean upward rotation range of motions were the smallest for Reach Out and Object Right (7.8° and 3.6°, respectively) followed by Object Left task with 22.5°. This small range of motions of upward rotation may have influenced subject control on movement execution.

From a clinical point of view it had been shown that subjects suffering from pathologies such as impingement and frozen shoulder have altered scapular kinematics. The averaged differences between asymptomatic and symptomatic groups is reported in the literature as 3.8° - 7.7° for scapular upward rotation [9, 50, 63, 85], 3.3° - 9.5° for posterior tilt [9, 50, 53, 63], and 4.4° - 5.2° for external rotation [50]. The differences found in the current study between constrained and functional motion may indicated that functional tasks may be more sensitive to identify altered scapular kinematics patterns.

To further investigate scapular angle differences a comparison of the average angle differences between the constrained and functional humeral motion was executed (Figure 2.4). It was discovered that the six tasks can be divided into two groups, which carried similar patterns within each of the three scapular rotations. The first group (group

1) consisted of Belt, Shelf and Overhead tasks and the second group (group 2) consisted of Reach Out, Object Right and Object Left tasks. Throughout most of scapular internal rotation, constrained angles were found to be larger than the functional angles in group 1. However, the opposite pattern was observed in group 2. Most of scapular upward rotation and posterior tilt functional angles were larger than the constrained angles in group 1, whereas, the opposite was true in group 2. Further investigation of the data revealed that group 1 had a larger range of humeral elevation angle relative to group 2. This may indicate that functional tasks with a target lower than shoulder height may have a different muscle recruitment and coordination patterns than functional tasks with a target above shoulder height, given that the constrained data used for the interpolation had the target above shoulder height for all the trials. Sainburg et al. found that when starting from different locations to reach to the same end point target the path was similar but muscle recruitment and coordination patterns were different [88].

Pearl et al. [78] found that when naturally reaching overhead, humeral elevation was preferentially executed in the scapular plane. The most common test for shoulder behavior utilized constrained humeral elevation, typically in the scapular plane [4, 16, 18]. One question is whether humeral elevation variability between-subject was different when executing a functional movement when compared with that of constrained humeral elevation in the scapular plane? The between-subject *CMC* values for constrained humeral elevation in the scapular plane were found to be similar to Shelf and Overhead task (Table 2.2). In the constrained trials the scapular plane is defined as 30°-45° relative to the thorax at a specific humeral elevation usually 90°, but during elevation the scapula slides and rotates, altering the actual scapular plane position [78]. Studies have found differences in scapular kinematics related to the plane of humeral elevation [64, 68] which may lead to higher between-subject variability in the constrained humeral elevation. Based on the observed variability, it appeared that functional tasks such as the Overhead or Shelf also can be used for shoulder evaluation between subjects. In the present study design, subjects performed each tasks once to avoid fatigue, therefore, within subject reliability testing could not been executed for all functional tasks. It was found that scapular kinematics was reliable under constrained protocols in the frontal, scapular and sagittal planes [99]. To the best of our knowledge no reliability tests have been conducted on scapular kinematics while performing functional shoulder protocols. However, functional movements such as the tasks in this study are used more frequently in daily activities than constrained motion. This study did not try to validate a specific functional task.

One of the main issues when using surface sensors methods to measure scapular and humeral kinematics is skin artifact. Karduna et al.[39] show that RMS error for scapular posterior tilt, upward rotation and external rotation was 6.2°, 4.5° and 5° respectively. Ludewig et al.[49] found that RMS error for humeral plane of elevation, elevation and external rotation was 3.8°, 3.1° and 7.5° respectively. For both constrained and functional protocols the same surface sensors were used, so the error related to skin artifact should be consistent in both protocols. Not randomizing the order between the constrained and functional protocols may have introduced error related to fatigue and sensor slip. We believed that fatigue was not an issue in this study protocol because the subject had three minutes rest between trials and the functional testing consisted of only six arm motions. Regarding the sensor slip as the trial progress which may contribute to the error between the two protocols, we believe it was negligible. These methods have been used for a while in our laboratory and were tested for reliability [102]; furthermore the functional tests consisted only six tasks of which four were less than 90° of arm elevation, less extreme range of motion. Another reason for the differences between the constrained and functional shoulder movements may be caused by differences in the third rotation, humeral external/internal. McClure et al. [64] showed that at 90° of arm elevation while performing full range of humeral external/internal rotation scapular orientation could have changed by up to 15°. In the present study the third humeral rotation was controlled in the constrained trials but not in the functional testing. The RMS difference for the humeral third rotation, internal/external rotation, was calculated for each functional task and its corresponding interpolated constrained data. The RMS differences were 7° - 14° for the different tasks. Ludwig et al.[49] showed RMS error of 7.5° when using surface sensors in comparison to bone pins when measuring humeral external/internal rotation during elevation in the scapular plane, however, the results were based on one subject. All the motions in this study were performed in mid range of the humeral internal/external rotation not at the end range of the motion, which may have decreased the error. Another reason may be related to shoulder torque. McQuade and Smidt [66] found that differences in shoulder load have influenced scapular rhythm. In the constrained position the elbow was extended during the whole range of motion versus functional movement, when the elbow was flexed to varying degrees for different tasks. This would have created differences in shoulder torque which may have influenced muscle activation and coordination levels. During functional testing the thorax was not controlled (for example trunk flexion during the Reach Out task) whereas in the constrained trials the thorax was restricted to the frontal plane, which may have altered scapular position and orientation. It has been shown that different thorax position (erect and slouched postures while in seated position) altered scapular kinematics and muscle force output [22, 40].

Humeral elevation angular velocity was controlled in the constrained trials to 40°/s but was not controlled during the different functional tasks with averaged angular velocities of 30°/s - 120°/s for the different tasks. However, Fayad et al. [20] found that there were no significant differences in scapular kinematics at two self selected, low and high, velocities. If the angular velocities of the functional trials were controlled to match the constrained trial averaged angular velocity the functional task would have lost its natural pattern and becomes partially constrained. In this study we chose to constrain the motion by using verbal feedback to constrain the elbow motion and trunk motion. It may be that if a less or more constrained methods were used to quantify scapular kinematics scapular angle differences would have been different.

CONCLUSIONS

The findings of this study showed that differences were evident in scapular behavior between constrained and functional motion. The largest differences were observed in scapular upward rotations. Tasks that involved small humeral elevation and/or involved trunk flexion had higher angle difference relative to the task's range of motion.

Variability between-subject in constrained scapular plane movement is similar to the variability in Overhead and Shelf functional motion. This may lead to the first conclusion that care needed to be taken when comparing, generalizing and normalizing scapular kinematic data drawn from constrained humeral movements and applying it on functional humeral movement, in healthy populations. Second, based on the results from this study it seems that it is not always necessary to use constrained humeral elevation in the scapular plane to measure scapular behavior because the between-subject variability is the same or in some cases larger than overhead functional tasks.

BRIDGE

The first study provided evidence that there are differences in scapular kinematics while performing constrained arm elevation and functional movements. Furthermore, it was also evident that the between-subjects scapular kinematics variability while performing constrained arm elevation in the scapular plane is not necessarily smaller than the between-subjects variability involving overhead functional tasks. This led us to the conclusion that when investigating scapular kinematics in a specific occupation it is preferable to use functional tasks to learn more about their scapular behavior in the workplace. Moreover, based on the literature review there is a need to validate an ambulatory device to measure humeral elevation exposure in the workplace. Chapter III describes the validation of a commercially available triaxial accelerometer for the construction of humeral elevation angles under static and dynamic conditions.

CHAPTER III

VALIDATION OF TRI-AXIAL ACCELEROMETER FOR THE CALCULATION OF ELEVATION ANGLES

In the following study all data collection was performed by me. Dr. Karduna assisted with statistical analysis, interpretation of the results, and manuscript editing. Dr. Laurel Kincl assisted with data collection and manuscript editing. Keely Zodrow assisted with data collection and data reduction.

INTRODUCTION

Shoulder pathologies are included under the broad term of musculoskeletal disorders, which is defined by the United States Department of Labor as an injury or disorder of the muscles, nerves, tendons, joints, or cartilage when the event or exposure leading to the injury or illness is bending, reaching, twisting, overexertion, or repetition. The outcome may be sprains, strains, tears, soreness and pain [10].

The United States Department of Labor has also reported that in 2005 there were a total of 1.2 million injuries and illnesses requiring days away from work in the private industry, with 30% due to musculoskeletal injuries. The event that resulted in the longest absences from work was repetitive motion, with shoulder injuries being responsible for more lost work days than any other joint [10]. Additionally, Ohlsson et al. [75] found that chronic exposure to arm elevation higher than 60° during a work day is associated with higher rates of shoulder injury, while Svendsen et al. [95, 96] and Punnett et al. [81] found that workers exposed chronically to arm elevation higher than 90° are more susceptible to shoulder injury.

Three main physical risk factors for musculoskeletal disorders have been identified in the workplace: force (intensity and duration), repetition, and posture (awkward and constrained) [5]. The assessment of occupational exposures to these risk factors in field settings is very challenging. Three methods are commonly used to determine exposure: (1) self reporting, questionnaire and interview, (2) observational methods and (3) direct measurements [15, 44]. The first two methods are subjective whereas, direct measurement is objective and provides precise measurements; hence, it is usually preferred. However, factors such as the cost of equipment, need for trained technicians, time consuming equipment setting and proper calibration, unsafe work environments, constrained recording area, and limited recording time, limits the usability of some of the high end or sophisticated systems in the workplace.

To overcome these disadvantages, low cost, body-mounted transducers combined with data loggers capable of whole day ambulatory recordings are used. For upper extremity exposure measurements, goniometers [76] and inclinometers [31] have been used to estimate the arm elevation angles. An inclinometer is a transducer that measures the elevation/inclination angle relative to gravity. Different types of transducers have been developed and are used to measure elevation angle exposure such as the abduflex [21, 97] consisting of mercury microswitches, Intometer [91] consisting of pressure transducers and distilled water, Physiometer [103] consisting of electrolytic liquid level sensors, and linear accelerometer [6, 19, 30, 31, 59, 70]. Linear accelerometers are commercially available and are commonly used in evaluation of segments' posture by means of uni-axial [76], bi-axial [7] and tri-axial [32] accelerometers.

However, many of these devices have limitations due to their construction. Most are big and clumsy with a cable connecting the transducers, which are placed on the body segment, and data loggers, which are usually worn on a belt at the waist. Some devices are complicated to mount and align with the coordinate system of the body segment. Others suffer from limited measuring range and/or low data collection sampling rates. Moreover, most of these devices are not available commercially. To the best of our knowledge there is one device with a built in data logger which is commercially available. The Virtual Corset (Microstrain Inc. VT, USA) is a pager-sized, battery powered, tri-axial linear accelerometer with an integrated data logger and no associated cables. However, the main problems with linear accelerometers are their sensitivity to linear acceleration and assessment of only two axes of rotation. Any linear acceleration besides gravity will bias the calculated elevation angles. To better understand the use of the Virtual Corset and the data that can be obtained with this device on the arm, laboratory testing was completed. The purpose of this study is to test and evaluate the Virtual Corset's accuracy for reconstructing elevation angles from acceleration data, in static and dynamic conditions using the acceleration data from one axis and three axes.

METHODS

The first step was to derive an equation to convert accelerometer data to elevation angles. During static positioning, the resultant acceleration detected by a tri-axial accelerometer is gravity (g). In the current study the elevation angle was defined as the angle between the z axis of the tri-axial accelerometer and the resultant gravity vector (Figure 3.1). Two approaches were selected to calculate the elevation angle. The first is with the use of data from only one accelerometer (z axis):

$$\theta = \cos^{-1}\left(\frac{z}{g}\right) \qquad (1)$$

The second is with the use of data from all three accelerometers (x y z axes). For this approach, the first step is to solve for the length a:

$$\mathrm{a} = \sqrt{x^2 + y^2} \qquad (2)$$

Next θ, is given as:

$$\theta = \tan^{-1}\left(\frac{\mathrm{a}}{z}\right) \qquad (3)$$

Combining equations 2 and 3 yields equation 4, which expresses the elevation angle as a function of the data from all three accelerometers:

$$\theta = \tan^{-1}\left(\frac{\sqrt{x^2 + y^2}}{z}\right) \qquad (4)$$

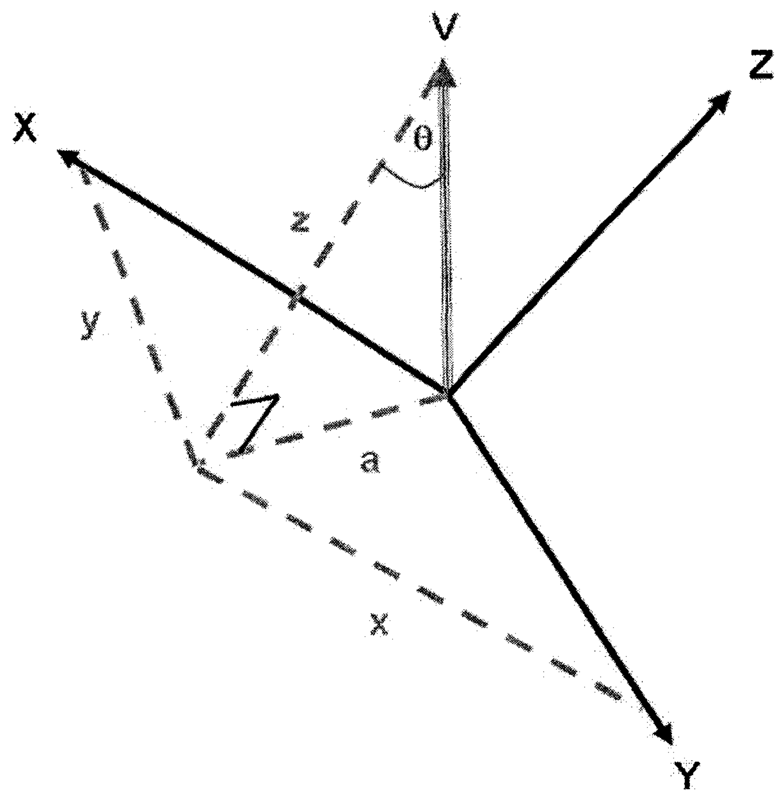


Figure 3.1. Vector projection on the XY plane.

Instrumentations and Calibration

The Virtual Corset (Microstrain Inc,VT, USA) is a pager-sized (6.8 cm by 4.8 cm by 1.8 cm), battery powered tri-axial accelerometer with an integrated 2 Mb data logger, with a total weight of 72 g and no associated cables. Since this device was originally designed for use with the trunk, the standard output was the projection angles of flexion and lateral bending. The manufacturer modified the internal software so that the device would save the raw data from the three accelerometers for this study. This device is constructed from two dual axis accelerometers, ADXL202E (Analog Device, MA, USA) ± 2g and 0.2%

nonlinearity, with a sampling rate of approximately 7.6 Hz. In the present study four Virtual Corsets were tested under static conditions and three were tested under dynamic conditions.

The Virtual Corset's raw data output is acceleration in bits. To convert this acceleration to g's (gravitational units) each Virtual Corset was calibrated using a customized jig, which rotates around three orthogonal axes. The minimum and maximum values from the raw data for each acceleration axis were registered and used to calculate the gain and offset of each axis for the different Virtual Corsets. The gain was calculated by subtracting the minimum value from the maximum value and dividing the result by two. The offset was calculated by averaging the maximum and minimum values. Using the calculated gain and offset the raw acceleration data were converted from bits to g's. Equation 4 was then used to calculate elevation angles.

In the static testing, a PRO 3600 digital protractor (Macklanburg, OK, USA), with a reported accuracy of 0.1°, was used to validate the Virtual Corset. The Virtual Corset and the digital protractor were attached to a vise, which could rotate about three axes similar to the shoulder joint. The International Society of Biomechanics recommend a Y-X'-Y'' Euler sequence to describe humeral rotations. The first rotation (plane of elevation) describes the plane at which an arm elevation is occurring. The second rotation represents the actual arm elevation and the third rotation represents the internal/external rotation of the arm [116]. In the present study only the horizontal axis (which represents humeral elevation rotation) and the vertical axis (which represents humeral plane of elevation rotation) were simulated.

For dynamic testing, a SW22B Wirewound precision single turn potentiometer (ETI Systems Inc, CA, USA), with a linearity tolerance of ± 0.5%, was connected to an aluminum arm to create a pendulum. The Virtual Corset was attached to the pendulum arm at different distances to validate it under different dynamic conditions.

Data Collection

Static: When measuring acceleration with a tri-axial accelerometer under static conditions the resultant vector is the gravitational acceleration, thus, equations 1 and 4 can be used to calculate the elevation angle relative to gravity. To validate equations 1 and 4, the Virtual Corset was mounted on a vise which could be rotated through 360° of elevation and 90° of plane of elevation (Figure 3.2), where 0° of plane of elevation represents the frontal plane and 90° of plane of elevation represents the sagittal plane. The digital protractor was attached to the vise to identify the elevation angles at 0° of plane of elevation. The vise was rotated through 360° of elevation in 10° increments. At each elevation angle, the plane of elevation was varied from 0° to 90° in 15° increments. Each position was held for 10 seconds and the acceleration data were recorded and averaged for each axis. Elevation angles were calculated using equations 1 and 4. This procedure was repeated at two different days for each Virtual Corset.

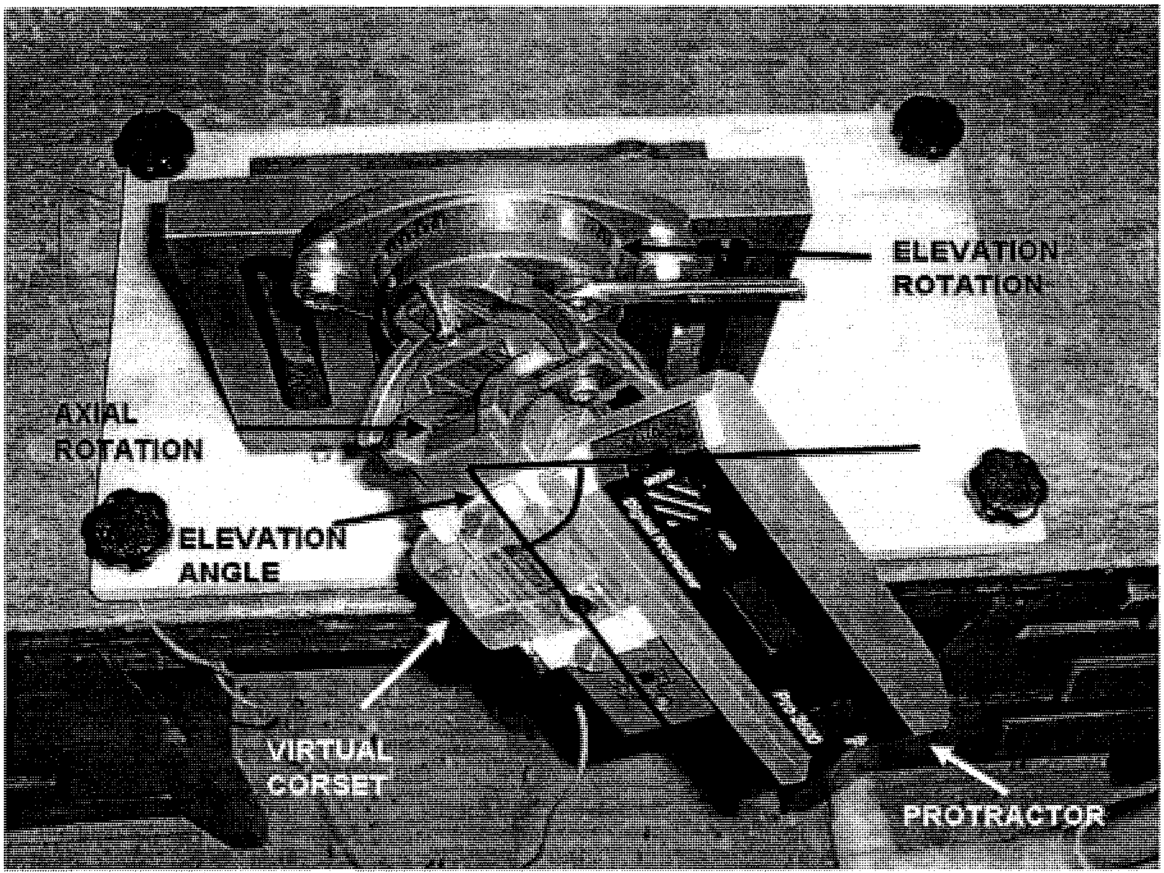


Figure 3.2. Static test setup

Dynamic: Linear accelerometers are sensitive to linear acceleration. Hence, any linear acceleration acting on the system besides gravity will result in an error of the predicted elevation angle. To predict the error in elevation angle due to linear acceleration, the angle between the actual resultant and gravity acceleration vectors was calculated. If these two vectors are the same, then the angle should be zero. The cross product equation was used to find the angle between the two vectors.

To calculate the predicted angle error in a controlled environment we used a pendulum, which introduced high and variable levels of angular velocities and accelerations. The pendulum was chosen because it was relatively close to in vivo movement of a body segment, in that it rotates around an axis (joints) with changing angular velocities and accelerations. For angular motion, the resultant linear acceleration is the sum of the gravitational (g), radial (a_r) and tangential (a_t) acceleration vectors (Figure 3.3). Radial acceleration is the product of the angular velocity and the radius and the tangential acceleration is the product of the angular acceleration and the radius. The error (β) due to these non-gravitational accelerations is a function of the angular position (θ), velocity (ω) and acceleration (α) and distance from the virtual corset to the axis of rotation (r):

$$\beta = \sin^{-1}\left[\frac{(\alpha r + g\sin\theta)\cos\theta - (\omega^2 \mathrm{r} + \mathrm{g}\cos\theta)\sin\theta}{\sqrt{(\alpha r + g\sin\theta)^2 + (\omega^2 \mathrm{r} + \mathrm{g}\cos\theta)^2}}\right] \qquad (5)$$

To check the validity of this equation to predict the actual angle error, the Virtual Corset was mounted on the pendulum's arm at nine different distances from the pendulum's axis of rotation to the estimated center of rotation of the Virtual Corset (1 cm error) as follow, 0 -10 cm in 2 cm increments and 10 – 25 cm in 5 cm increments. In each trial the pendulum's arm was released from an angle of -105° of elevation and data were collected from the Virtual Corset and potentiometer for 15 seconds and saved. The potentiometer data were sampled at 1000Hz. These settings were repeated for each of the Virtual Corset at three different positions, which represent different planes of elevation, frontal, scapular (35° anterior to the frontal plane) and sagittal planes. Synchronization between the Virtual Corset and the potentiometer was achieved by searching and matching the minimum and maximum peak angles for each cycle of the Virtual Corset and the potentiometer. The actual angle error and the predicted angle error were compared.

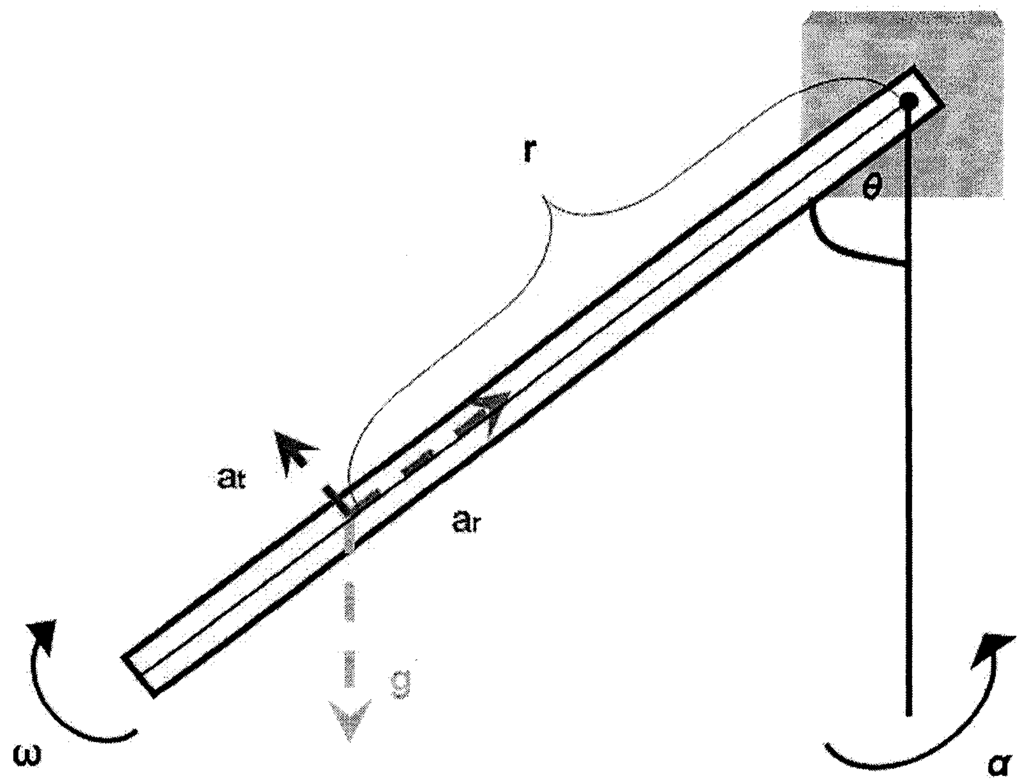


Figure 3.3. Dynamic test setup

To validate the use of the Virtual Corset beyond the pendulum setting using human movement, data of three tasks from a previous reaching study [2] were used. In this reaching study the kinematic data were collected from 20 subjects at a sampling rate of 120 Hz using a Polhemus magnetic tracking system and no Virtual Corset data was collected. The data of humeral elevation were calculated relative to the global coordinate system (gravity based). In the first task subjects raised and lowered their arms for a total of seven times, with each cycle lasting approximately six seconds (Constrained). Then two unconstrained reaching movements were completed: one reaching overhead (Overhead) as high as possible and one reaching to a seat belt (Belt) on the contralateral side. These data were used to calculate the range of predicted errors in vivo for controlled and functional movements (equation 5).

Data Analysis

For the static trials, root mean square (RMS) errors were calculated for each position between the known inclination angles and the calculated elevation angles using the Virtual Corset data of only one accelerometer (equation 1) and of all three accelerometers (equation 4). For each Virtual Corset the calculated RMS error and angle difference pattern using one axis were compared with the calculated RMS error and angle difference pattern using all three axes. Moreover, data were compared between the different Virtual Corset and between days.

For the dynamic trials errors between the Virtual Corset calculated elevation angle and the potentiometer angle were determined for each Virtual Corset at the different locations. This error was used to validate equation 5. Also, the RMS and the absolute maximum predicted angle errors of the subjects were calculated and averaged for each task of the reaching study.

RESULTS

For the static condition, the RMS error of the calculated elevation angles using the data from three accelerometers was found to be less than 1° in both trials for all the Virtual Corsets (Figure 3.4).

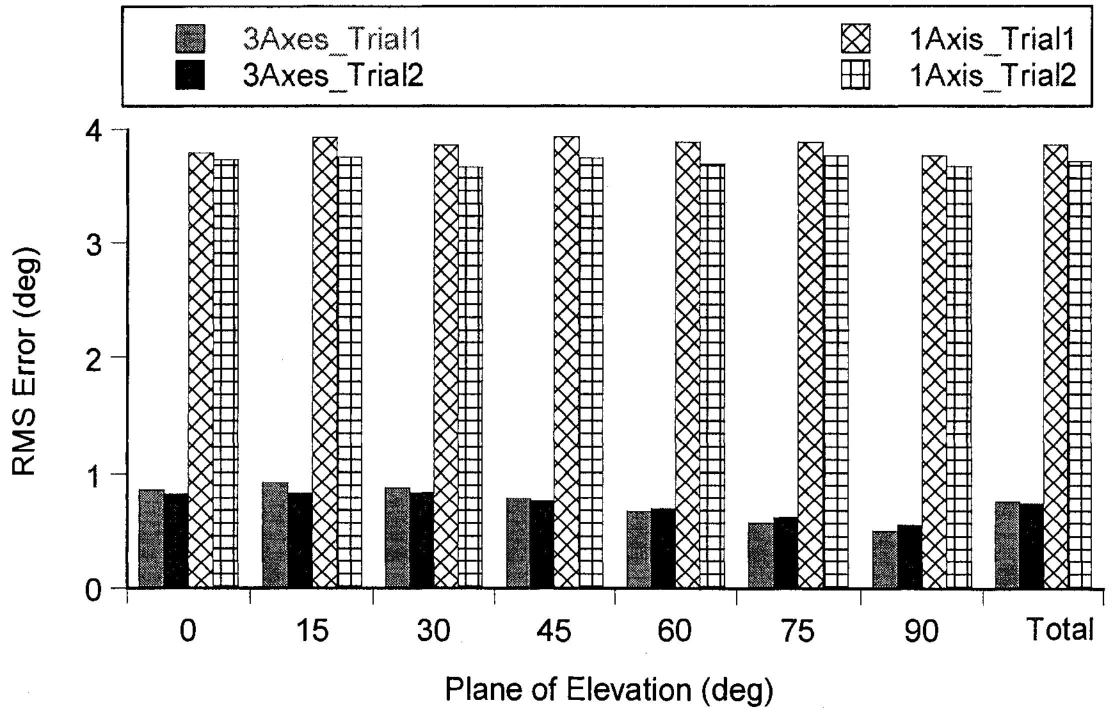


Figure 3.4. Calculated RMS error of elevation angles using three axes and one axis at different planes of elevation in two different trials

Also, the maximum difference between the calculated and the actual elevation angles was less than 2° (Figure 3.5A). The calculated angle error using the data from one accelerometer showed a higher total RMS error, less than 4°, (Figure 3.4) with the largest differences, 14°, close to 0° and 180° of elevation (Figure 3.5B).

In the present study setting, the plane of elevation rotation angles did not appear to have a large influence on the error magnitude of the calculated angles; however, each Virtual Corset had its own pattern.

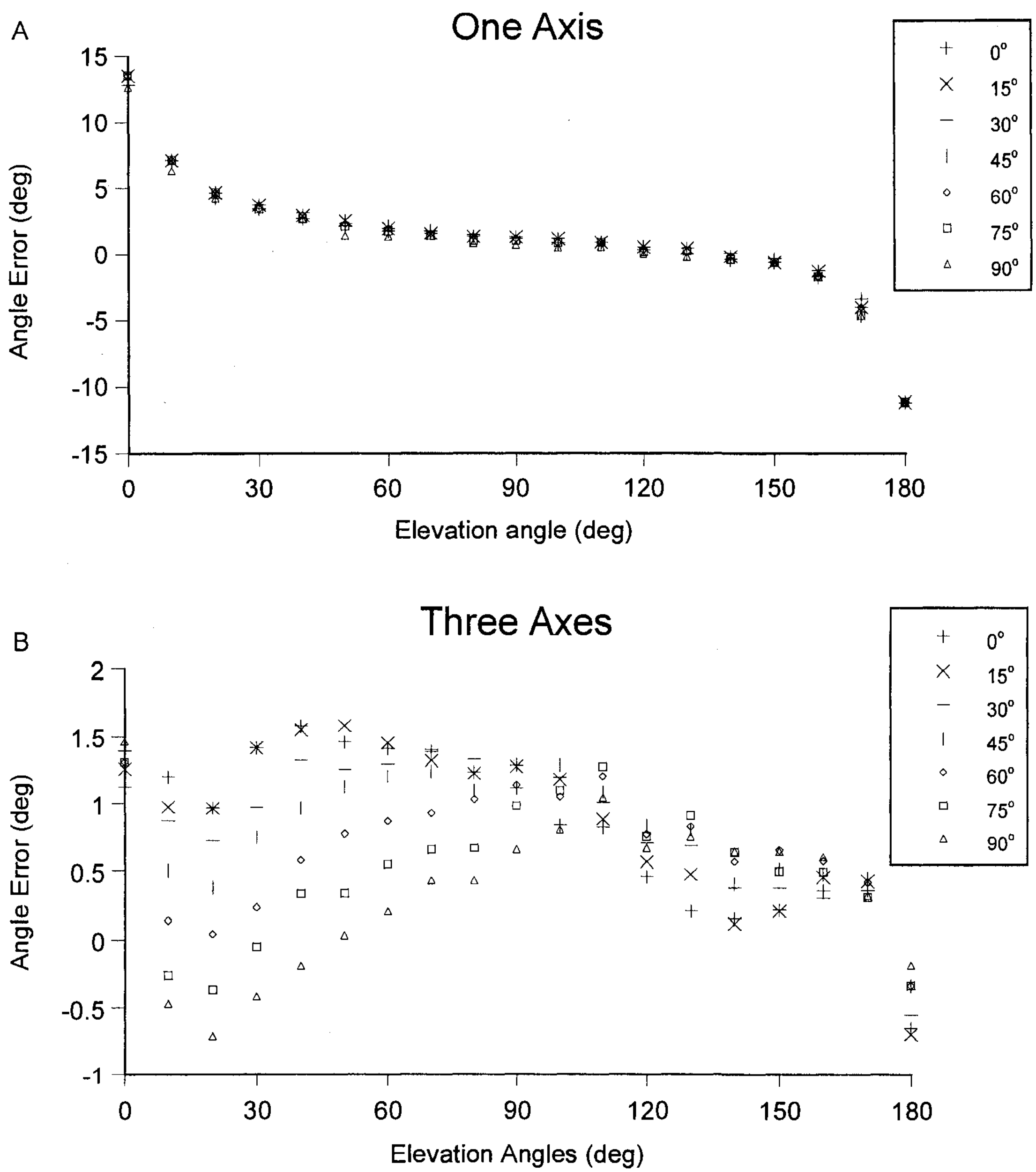


Figure 3.5. Difference error of elevation angles at different planes of elevation, when using data of one axis (A) and when using data of three axes (B).

Under dynamic conditions the calculated elevation angle error was increased as the radius increased and as the angular acceleration increased (Figure 3.6).

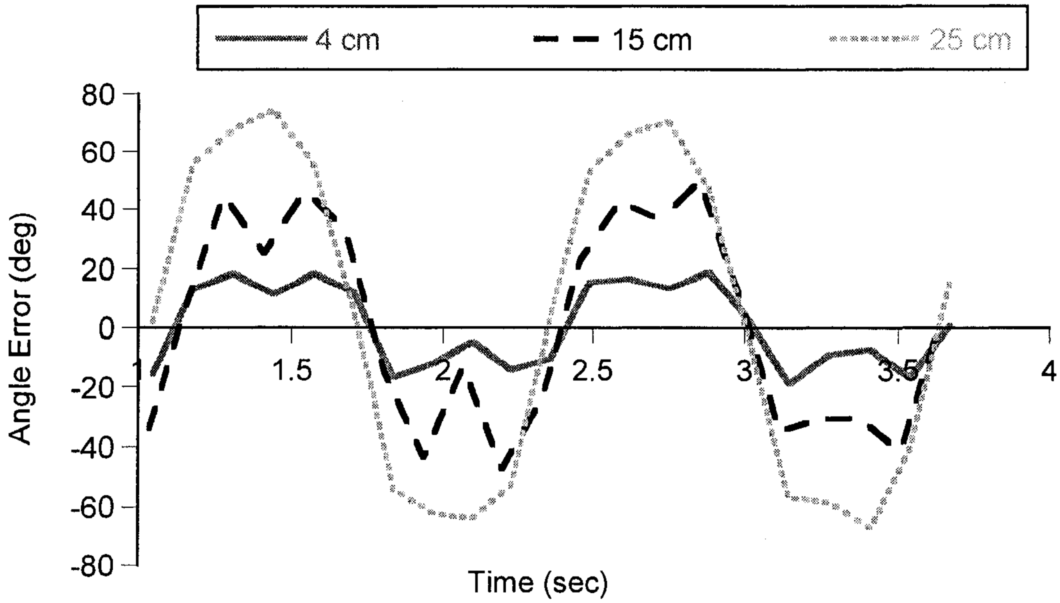


Figure 3.6. Difference error between the potentiometer calculated angle and the Virtual Corset calculated angle at three different radii

The maximum angle error difference ranged from 10° to 80° based on the radius. However, it was found that angle errors followed similar pattern as of the angular acceleration, high angle errors occurred mainly at very high angular accelerations. The calculated predicted elevation angle errors from the pendulum's data were found to be similar to the Virtual Corset calculated elevation angle errors with a RMS difference of 3° at radii of 10 cm and 25 cm (Figure 3.7).

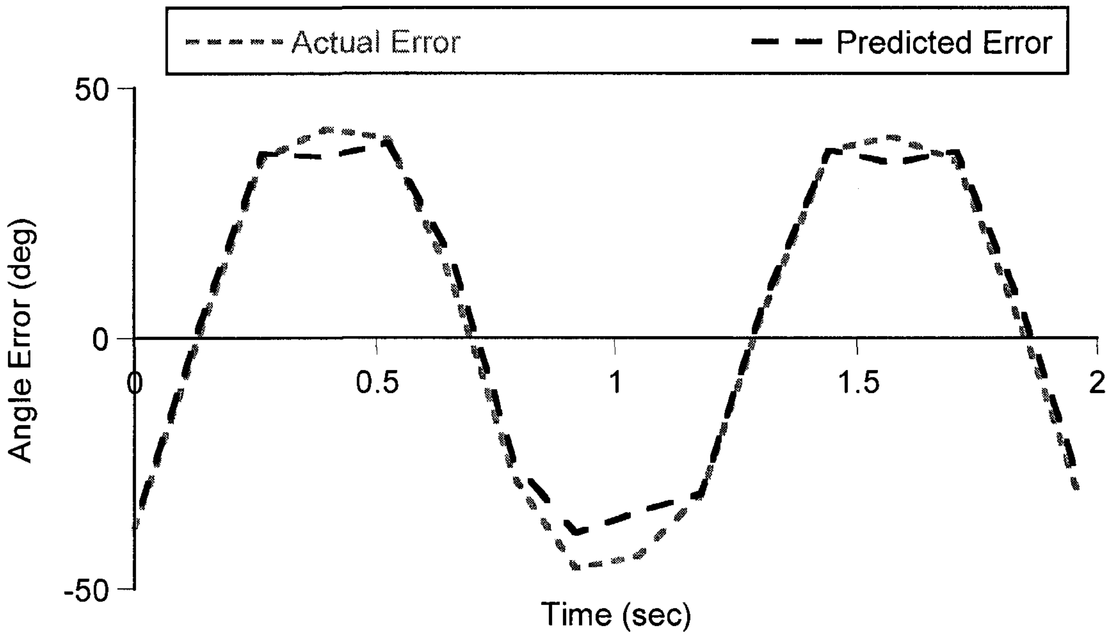


Figure 3.7. Difference between the actual angle error and the predicted angle error at a radius of 20cm

The prediction equation was used on data sets from a previously collected reaching study using a radius of 10cm (an estimated distance of the deltoid tuberosity to the center of rotation of the humerus). Averaged RMS and absolute maximum angle error, angular velocity and angular acceleration were calculated. Comparing the pendulum and in-vivo (reaching) data the controlled arm elevation had the lowest averaged RMS and maximum predicted angle errors. In all cases the angular velocity was lower in the reaching data by at least 190°/s, however, maximum angular acceleration was higher during the Overhead task (Table 3.1).

Table 3.1. Averaged angle error, angular velocity and acceleration at a radius of 10 cm during constrained arm elevation (Constrained), two functional tasks (Belt and Overhead) and pendulum.

	Constrained		Belt		Overhead		Pendulum	
	Max	RMS	Max	RMS	Max	RMS	Max	RMS
Angle error (deg)	9	1	12	3	22	5	38	23
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Angular Velocity (deg/s)	83	41	144	54	267	106	527	299
Angular Acceleration (deg/s^2)	933	112	1351	314	2892	554	2109	1556

DISCUSSION

The Virtual Corset was originally designed to measure upper trunk orientation relative to the line of gravity describing it by using two projection angles, flexion/extension and lateral bending. The manufacturer (Microstrain inc.) reports a typical angles accuracy of ± 0.5° however; this error is associated with a motion range of ± 180° of trunk flexion and ± 70° of trunk lateral bending. This specific range might be suitable for the measurement of upper trunk motion but not for the shoulder joint. The shoulder is the most mobile joint in the body, not limited to two planes of elevation. Therefore, the manufacturer had customized the Virtual Corset output based on our needs to collect acceleration data, which then were converted to predict elevation angles relative to gravity. Our findings show that the Virtual Corset can be used to accurately predict arm elevation angles under static conditions. However, under dynamic conditions, researchers must understand the linear accelerations involved with the motions being studied and the placement of the Virtual Corset relative to the center of rotation of the joint.

Static Conditions

Hanson et al. [31] reported a mean angular error of 1.3° under static conditions which is close to what we have found in this study, RMS error of less than 1°. The RMS angle error was lower using the acceleration data of the three acceleration axes to predict the elevation angle relative to the use of one axis of acceleration. Maximum angle error was at different elevation angles for the different Virtual Corsets when using the data of the three accelerometers, however, when using the data of one accelerometer for the different Virtual Corsets the maximum error was repeatedly at 0° and 180° of elevation angles. Moreover, it was found that the plane of elevation had little influence on the angle error. Therefore, the use of tri-axial accelerometer is preferred, especially when measuring elevation angles between 0° and 180°. It might be reasonable to use uni-axial accelerometer to measure elevation angle when measuring shoulder exposure between 30° and 150°.

Dynamic Conditions

Linear accelerometers are sensitive to linear acceleration. Under static conditions, the only linear acceleration the accelerometers sense is the gravitational acceleration. However, if another linear acceleration is introduced, the resultant acceleration will no longer be gravity. In the present study, the radius and angular acceleration were found to have the largest influence on angle errors. The farther the Virtual Corset was located from the axis of rotation the higher the errors; larger radius increased the tangential and radial accelerations. The same is true for larger angular acceleration. The angular velocity did not have a large impact under these settings because the radial acceleration was parallel to the gravitational acceleration vector. It was also found that plane of elevation did not increase the angle error, similar to the results found under static conditions.

From a practical point of view, elevation angle RMS errors of 10° and above might be too big and meaningless to analyze. The ability to predict the angle error in elevation angle when linear accelerations, besides gravity, are introduced to the system will help the investigator to make a decision on how appropriate is the use of the Virtual Corset to measure exposure in specific job environment. The proposed prediction equation (equation 5) has the ability to predict the errors based on specific scenarios and hence make a decision on the appropriateness of the Virtual Corset. However, in this study there were two points in the pendulum arch that the equation could not predict the same error as the actual angle error in some cases by more than 30°. This happens close to ±90° where the pendulum is changing direction, the angular acceleration is at its peak and the angular velocity is close to zero. At these points the resultant acceleration components were very small, close to zero. Consequently, small changes in the data created large differences between the predicted error and the actual calculated error.

The pendulum is a unique form of motion, which includes very high angular velocities and accelerations, which under some of the scenarios the Virtual Corset might not be usable. Although, no actual in-vivo data were collected to calculate the error, the pendulum simulation is plausible as a model for in-vivo motion because of the angular range of motion and variety of angular velocities and accelerations. To check the utility of the Virtual Corset in measuring human arm elevation the prediction equation was applied to previously collected in-vivo data of reaching tasks. In these instances the higher angular accelerations were mainly at the onset of the motion. The average angular acceleration and velocities were much smaller in the reaching tasks than the pendulum. The high difference in the average angular acceleration may be related to the low sampling frequency of the Virtual Corset and the pendulum setting. In this setting the pendulum arm's velocity is the smallest at the end range, which provided more data points where the angular acceleration is the largest; hence it will bias the averaged angular acceleration. Increasing the sampling frequency might improve the accuracy of the Virtual Corset by increasing the data points collected under dynamic conditions. For the constrained motion the averaged RMS angle error was 1° and for the other two reaching tasks the averaged RMS angle error was less than 6°, and can be used to evaluate shoulder elevation in a work place. From these data it is clear that the use of the Virtual Corset for measuring ballistic motions such as baseball pitching is not practical with a reported internal rotation peak angular velocity of 8000 deg/s [112] and peak angular acceleration of 25000 deg/s^2 [34]. The estimated maximum angle error for this motion would be close to 90° and the peak resultant acceleration would be close to 200 g's, which is beyond the Virtual Corset measurement capacity of 2 g's. Nonetheless, it may be usable for measuring daily activities and occupational exposure at lower angular velocities and accelerations. Hansson et al. [30] found the upper arm angular velocity for material picking and assembly working to be 50°/s - 200°/s. Cleaning workers had higher upper arm angular velocity compared to office workers, 100°/s - 200°/s and 30°/s - 100°/s respectively [32]. Cote et al. [14] found the peak angular velocities and acceleration in the shoulder during hammering task to be 196°/s and 4149°/s^2 respectively. The estimated maximum angle error for the hammering task would be close to 40° and the peak resultant acceleration would be less than 2 g's, which is still in the range of the Virtual Corset. Estill et al. [19] found a low linear acceleration for the upper arm in industrial workers 0.32m/s^2 – 2.70m/s^2. These examples are still within the measurement range of the Virtual Corset. For each task or job where data collection is needed it is advisable to use equation 5 to estimate errors, which will help in determining the appropriateness of the Virtual Corset for that application.

Another potential limitation of the Virtual Corset is related to the perpendicular orientation between the two dual axes accelerometer, which are used to create the tri-axial accelerometer. Any physical offset between these two accelerometers may results in increase in angle error. Our results show low error under static conditions, which would imply good positioning of the accelerometers of the Virtual Corsets tested. Other practical considerations for the use of the VC in occupational settings include the memory and the software launching of the device. Under the configuration utilized in the present study, the Virtual Corset is capable of collecting data for 6 hours, which is less than a typical full work day. An increase in the data logger memory size would extend the time of data collection and will be more useful. A start and end switch on the device for the data collection would make the use of the Virtual Corset easier in the field and for the data analysis. Currently, the device begins collecting data from the moment the battery is placed in the unit.

Finally, the most mobile joint in the human body is the shoulder. The output of the Virtual Corset is the elevation angle relative to gravity; it cannot detect the rotation around the gravitational axis. To overcome this issue new systems have been developed which incorporate triaxial accelerometers and gyroscopes. However, these systems suffer from an increase in error as a results of the gyroscopes cumulative drift around the vertical axis and the alignment of the gyroscopes sensors to the body segments [52].

CONCLUSIONS

The Virtual Corset (tri-axial accelerometer) can be used to accurately reconstruct elevation angles under static conditions. In order to improve data collection qualities under dynamic conditions the following recommendations are offered:

1. Locate the Virtual Corset as close as possible to the joint center of rotation (to reduce the radius).
2. Estimate the maximum and average angular velocity and acceleration of the task.
3. Determine the typical and maximal range of humeral elevation angle.
4. Use equation 5 to determine whether the expected errors are within acceptable tolerances for the given experiment.

BRIDGE

The second study provided evidence that the triaxial accelerometer (Virtual Corset) can be used to reconstruct humeral elevation angles under static conditions. Under dynamic conditions it has been found that the error increased with respect to angular velocity and acceleration, radius and elevation angle. However these results were collected a vise and a pendulum, which brings us to the third study purpose, which was to validate the Virtual Corset in-vivo. Chapter IV describes the validation of the Virtual Corset ability to collect elevation angles and identify correctly exposure parameters in 16 dental hygienists with respect to a high end motion capture system, a magnetic tracking device.

CHAPTER IV

IN-VIVO MEASUREMENT OF HUMERAL ELEVATION ANGLES AND EXPOSURE USING A TRIAXIAL ACCELEROMETER

In the following study all data collection was performed by me. Dr. Karduna assisted with statistical analysis, interpretation of the results, and manuscript editing. Michael Latteri assisted with data collection and data reduction.

INTRODUCTION

Numerous studies have assessed upper extremity motion in an attempt to quantify workers' exposures to risk factors for musculoskeletal disorders [21, 70, 80, 91, 96, 103]. In 2005 the United States Department of Labor reported that there were a total of 400,000 musculoskeletal injuries requiring days away from work in private industry. The event and joint that resulted in the longest absences from work were repetitive motion and the shoulder, respectively [10]. Both Svendsen et al. [95, 96] and Punnett et al. [81] found that workers exposed chronically to arm elevation angles higher than 90° were more susceptible to shoulder injury, whereas Ohlsson et al. [75] found that chronic exposure to arm elevation higher than 60° during a work day was associated with higher rates of shoulder injuries.

Three main physical risk factors for musculoskeletal disorders have been identified: force (intensity and duration), repetition, and posture (awkward and constrained) [5]. The measurement of occupational exposures in field settings is very challenging. Three methods are frequently used to determine exposure levels. The first two methods, survey and observational, are subjective whereas the third method, direct measurement, is objective and provides more precise measurements [15, 44].

Accelerometers are commonly used to estimate elevation angles for the upper extremity [6, 19, 30, 31, 59, 70]. However, several of these devices have limitations due to their construction. Some are cumbersome due to their dependence on hardwired cables connecting the transducers and the data logger. Others have a limited measuring range of motion and/or sampling rates. In addition, most of these devices are not available commercially. To the best of our knowledge there is one device with a built in data logger that is commercially available. The Virtual Corset is a triaxial accelerometer which has been previously validated under static and dynamic conditions [3]. Under static conditions the RMS error was below 1° whereas, under dynamic conditions the Virtual Corset is sensitive to angular velocity and acceleration along with the radius [3]. This device has not been validated under in-vivo conditions, to the best of our knowledge, which led us to the present study's question: how well can the Virtual Corset estimate elevation angles and exposure parameters in an occupational group (dental hygienist) relative to a magnetic tracking device? Studies have shown that 11% - 68% of dental hygienists suffer from musculoskeletal disorders in the upper extremity [1, 48, 71, 110, 111] and the prevalence of these musculoskeletal disorders increases with years of occupation [1, 48, [71, 82]. There is only one study reported in the literature that measured arm elevation exposure in dental hygienists using a videotape for observational analysis [57]. Thus far no studies have been done on dental hygienists using a direct measurement to quantify exposure to risk factors for shoulder musculoskeletal disorders.

METHODS

Subjects

Sixteen female dental hygienists with a mean age of 49.6 years (28 – 64 years), height of 166.8 cm (157 – 175 cm) and body mass of 71.1 kg (56.2 – 83.9 kg) were recruited. Inclusion criteria required practicing dental hygienists with a minimum of one year of work experience (actual experience range was 1.5 – 32 years). Exclusion criteria consisted of impairments in arm elevation range of motion (less than 120° of humeral elevation), current injuries to the shoulder or back, any surgical history of body parts in interest over the past two years as well as any diagnosed neurological disorders. Prior to participation, all subjects signed an informed consent form approved by the university's Institutional Review Board (IRB).

Instrumentation

Humeral elevation angles were collected with the Polhemus Liberty magnetic tracking device (Colchester, VT), which consisted of an electronics unit, a transmitter, one sensor and one digitizer. This device was interfaced with the MotionMonitor software program (Innovative sports Training, Chicago, IL). Data were collected at a rate of 120 Hz per sensor. The transmitter emitted an electromagnetic field that was detected by the digitizer and the sensor. The device's electronic unit determined the relative orientation and position of the sensors in space. Data analysis and interpolation were executed using LabView software (National Instruments, Austin, TX).

Humeral elevation data for the dominant arm were calculated from the acceleration data collected by the Virtual Corset [3]. The Virtual Corset (Microstrain Inc,VT, USA) is a pager-sized (6.8 cm by 4.8 cm by 1.8 cm), battery powered tri-axial accelerometer with an integrated 2 Mb data logger, with a total weight of 72 g and no associated cables. This device is constructed from two dual axis accelerometers, ADXL202E (Analog Device, MA, USA) ± 2g and 0.2% nonlinearity, with a sampling rate of approximately 7.6 Hz. Data analysis and interpolation were executed using LabView software (National Instruments, Austin, TX).

A simulated working station was created in the testing laboratory, which consisted of a dental hydraulic chair, dental light, and dental hygienist stool. A custom made manikin with dentures (Dental Hygiene Model: M-YNR-1560, Colombia Dentoform Corp. NY, USA) was secured to the dental chair using a strap (Figure 4.1).

Set-up and Digitization

A sensor was placed on the subject's dominant arm just above the medial and lateral epicondyles using a customized molded cuff attached by Velcro strips. A global coordinate system was established by mounting the transmitter on a rigid plastic base.

The transmitter was located behind the subject at the humeral sensor height, at a horizontal distance of 30 cm from the trunk.

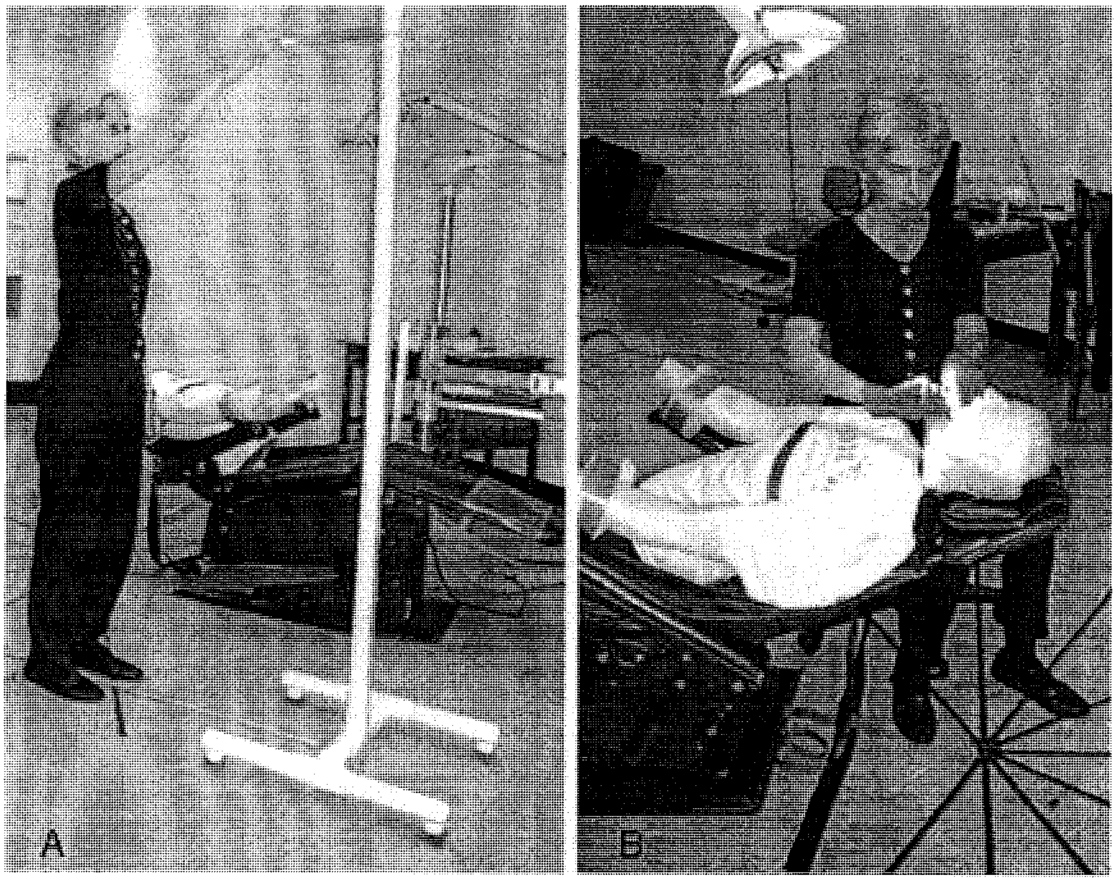


Figure 4.1. Reaching (A) and flossing (B) tasks.

During digitization, subjects were in their natural standing position. Anatomical landmarks were digitized for the humeral coordinate system (medial and lateral epicondyles and ulnar styloid process). The arbitrary axes defined by the magnetic tracking device were converted to anatomically appropriate embedded axes derived from the digitized bony landmarks. This was based on the ISB second recommendation for the humerus, taking the ulnar styloid process as the third point for the plane, with the elbow in 90° of flexion [116]. All landmarks were surface points and, therefore, could be located directly, except for the center of the humeral head. To locate the center of the humeral head another sensor was placed on the scapula. The center of the humeral head was defined as the point on the humerus that moves the least with respect to the scapula while moving the humerus through short arcs (< 45 degrees) of mid-range glenohumeral motion and was calculated using a least-squares algorithm [104]. After the digitization process, the raw data from the sensors were converted into anatomically defined rotations that could be displayed in real time using the MotionMonitor software. Standard matrix transformation methods were used to determine the rotational matrix of the humerus with respect to the global coordinate system. In the global coordinate system the Z axis was aligned with the line of gravity. Humeral rotations were represented using a standard Euler angle sequence (Y X' Y") in which the first rotation defined the plane of elevation, the second rotation described the amount of elevation and the last rotation represented the amount of internal/external rotation. In the current study only the humeral elevation angles were analyzed. Humeral elevation angles measured by an accelerometer are measured with respect to the line of gravity. Therefore in order to compare between the two devices, the humeral elevation measured by the magnetic tracking device was also reported with respect to the global coordinate system.

Following the digitization procedure for the magnetic tracking device, the Virtual Corset was mounted on the lateral side of the humerus just above the deltoid tuberosity using a double sided adhesive tape and secured in place using an under wrap Pre-taping foam (Mueller Sports Medicine, Inc. WI). The radius of rotation of the Virtual Corset had to be estimated in order to predict elevation angle errors as a result of dynamic motion. The center of the glenohumeral joint was estimated to be 3.1 cm below the acromion process using 2.3 cm as the averaged humeral head radius [65] plus 0.8 cm as the averaged height of the subacromial space [28]. The distance from the lateral aspect of the acromion process to the apex of the Virtual Corset was registered using a measuring tape. Subtracting the 3.1 cm from the Virtual Corset-acromion distance was assumed to be the accelerometers radius of rotation. The center of the glenohumeral joint was assumed to be the instantaneous center of rotation of the humerus with respect to the global coordinate system. This simplification may increased angle error as a result of trunk motion by shifting the center of rotation, however, in this study setting the subject had minimal trunk rotation. The elevation angle relative to the line of gravity for the Virtual Corset and magnetic tracking device (Zero gravity) were taken at the beginning of the testing. The subjects were in a seated position holding a 1.1 kg weight in their dominant hand. They were instructed to bend their trunk laterally, while their dominant arm hanging down freely [30]. At this position the arm is assumed to be aligned with gravity and may signify the differences the two devices read with respect to gravity.

Experimental Procedure

All testing was completed in a single session. Subjects started the experiment with a standardized warm-up procedure for the shoulder including Codman's pendulums and stretches for the rotator cuff muscles for both arms [2]. Following the warm-up procedure, subjects removed any object that would interfere with the magnetic tracking device data collection, such as jewelry and belts.

To quantify the ability of the Virtual Corset to identify exposure parameters in dental hygienists relative to the magnetic tracking device, data were collected under two conditions, reaching and flossing (Figure 4.1). For both conditions, the subject started with a synchronization task that was followed immediately by one of the conditions. The synchronization task involved subjects moving their arm back and forth 10 times (pendulum like) in the sagittal plane at a pace of 60 beats per minute (paced with a metronome). The two devices were synchronized by matching the peaks for each cycle of shoulder elevation (Figure 4.2). In the first condition following the synchronization task, subjects were in an upright standing position and performed a reaching task to a shelf at head height. The target was located in the sagittal plane at a horizontal distance of 80% of arm length and height of 50% of arm length above shoulder height. The target location was standardized and normalized for each subject based on anthropometrical measurements that were taken from each subject using a measuring tape [2]. In the flossing task, subjects were in a seated position in the simulated work station and were instructed to perform full mouth flossing with the technique used in their daily work routine (figure 4.1B). Each task was performed twice.

Data Reduction/Statistical Analysis

The cumulative error in the simulated dental hygienist's work station on the magnetic tracking device was measured and calculated. The simulated work station was modified to reduce the error by replacing the dental chair metal head support with wood; also the manikin, used as a replacement for patient, was made out of fiberglass.

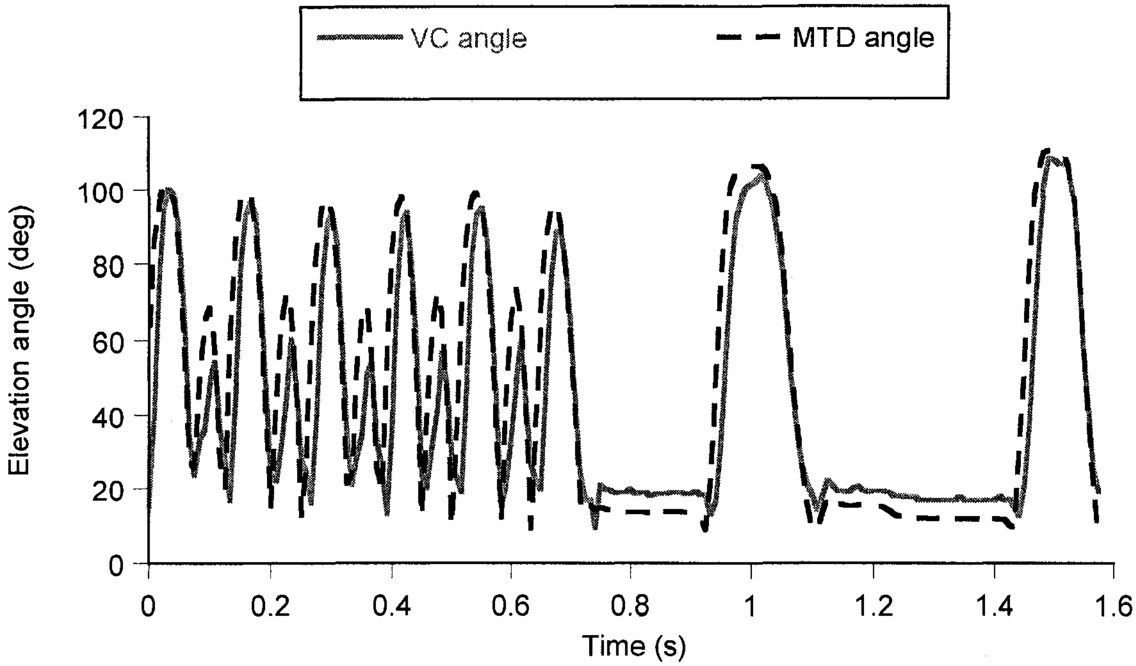


Figure 4.2. The synchronized pendulum motion followed by the two reaching tasks of the Virtual Corset (VC) and the magnetic tracking device (MTD).

The highest RMS angle error for the magnetic tracking device at this simulated work station was 1.4°. Also, the Virtual Corset angle error for each task was predicted using equation 1. This equation was validated in a prior study [3]. The error (β) was estimated as a function of the angular position (θ), velocity (ω) and acceleration (α) and distance from the virtual corset to the axis of rotation (r):

$$\beta = \sin^{-1}\left[\frac{(\alpha r + g\sin\theta)\cos\theta - (\omega^2 r + g\cos\theta)\sin\theta}{\sqrt{(\alpha r + g\sin\theta)^2 + (\omega^2 r + g\cos\theta)^2}}\right] \qquad (1)$$

To quantify the differences in elevation angles between the Virtual Corset and the magnetic tracking device in the reaching task, subjects' range and average humeral elevation angles were calculated. A paired t-test was conducted to determine if there was a significant difference between the two devices. The data of the two reaching trials were averaged prior to data analysis. In the flossing task, exposure parameters were used to compare between the two devices. The chosen exposure parameters were Jerk analysis and percent time above 20°, 40° and 60°. The Jerk is a parameter describing the repetitiveness of a task and was defined as the percentage of the cycle time spent in time sequences shorter than 1 second within the same exposure bin of 10°. A larger Jerk value indicates a more dynamic exposure pattern [58, 70]. A paired t-test was conducted to determine if there were significant differences for the Jerk variable between the two devices. The data of the two flossing trials were averaged before performing separate two-way ANOVA with repeated measures, with percent time above as the dependent variable and two independent variables. The independent variables were Device (Virtual Corset and magnetic tracking device) and Position (20°, 40° and 60°). Also, a Pearson correlation test was run to assess correlation between the two devices. Intra-subject repeatability of these different dependent variables was quantified with the intraclass correlation coefficient, ICC (3, 1) and standard error of measurement (SEM).

RESULTS

Averaged across subjects, the zero gravity position measured by the Virtual Corset and the magnetic tracking device were 6.7° (3.8°) and 8.3° (4.7°), respectively. Intra-subject

ICC values for the dependent variables ranged from 0.61 to 0.99 indicating good to high reliability (Table 4.1).

Table 4.1. Mean and Intra-subject reliability for the dependent variables of the reach task, average humeral elevation angle (Average) and range of humeral elevation (Range) and for the floss task, Jerk, % time above 20°, % time above 40° and % time above 60°.

		Virtual Corset			Magnetic Tracking Device		
Task		Mean	ICC	SEM	Mean	ICC	SEM
Reach	Average (deg)	56.4	0.7	3.6	65.8	0.71	3.8
	Range (deg)	95.2	0.96	1.3	99.3	0.74	2.5
Floss	Jerk (%)	25.9	0.61	4.5	21.9	0.71	4
	% time above 20°	71.9	0.99	2.4	78.6	0.99	2.1
	% time above 40°	25.8	0.96	4.4	35.2	0.96	5.3
	% time above 60°	7.8	0.87	2.6	11.7	0.9	3.3

Significant differences were found in the reaching tasks for the average humeral elevation angles ($p < 0.001$) and the range of humeral elevation ($p = 0.019$) between the Virtual Corset and the magnetic tracking device (Figure 4.3 – 4.4). The means for the averaged humeral elevation angle of the Virtual Corset and the magnetic tracking device were 56° and 66°, respectively. The means for the range of the humeral elevation of the Virtual Corset and the magnetic tracking device were 95° and 99°, respectively.

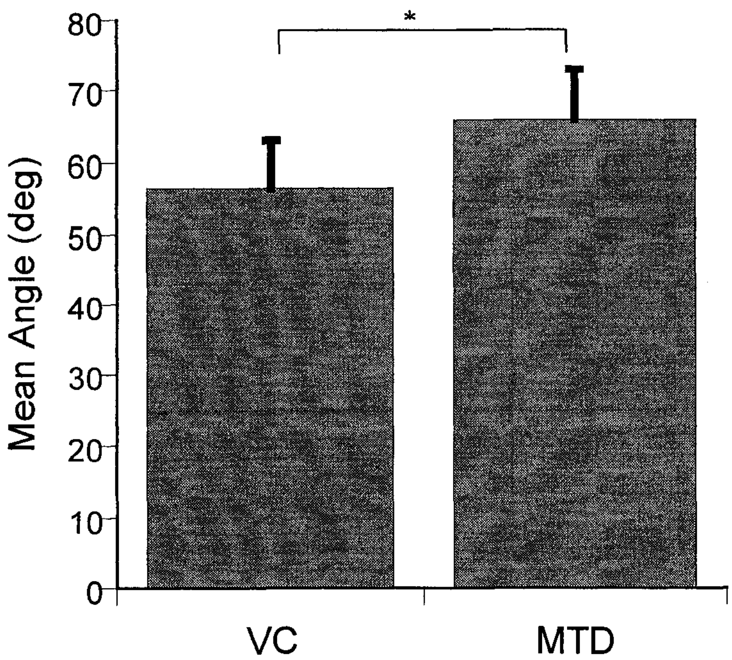


Figure 4.3. Mean humeral elevation angles between the Virtual Corset (VC) and the magnetic tracking device (MTD) for the reach task. * $p < 0.05$

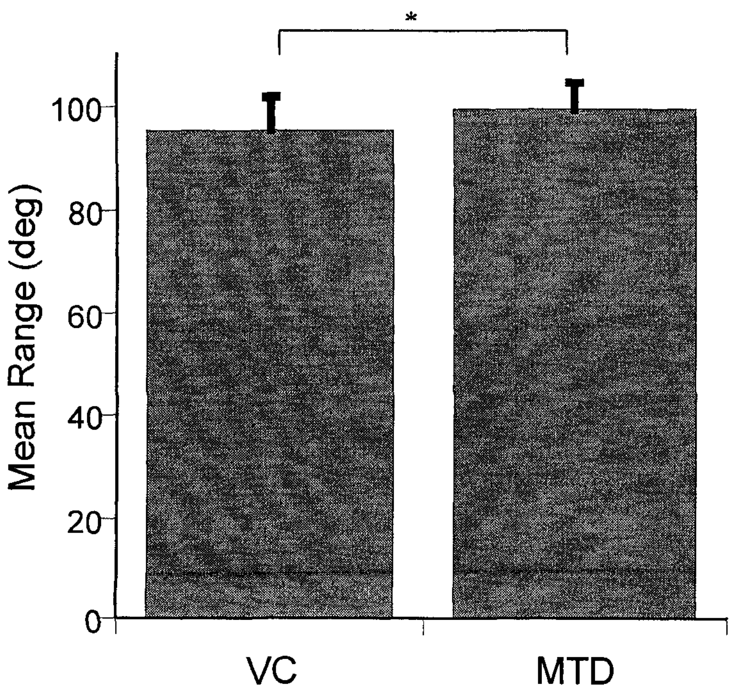


Figure 4.4. Averaged range of humeral elevation angles between the Virtual Corset (VC) and the magnetic tracking device (MTD) for the reach task. * $p < 0.05$

High correlation (r = 0.85) was found for the averaged humeral elevation angle and moderate correlation (r = 0.44) for the range of humeral elevation (Figure 4.5).

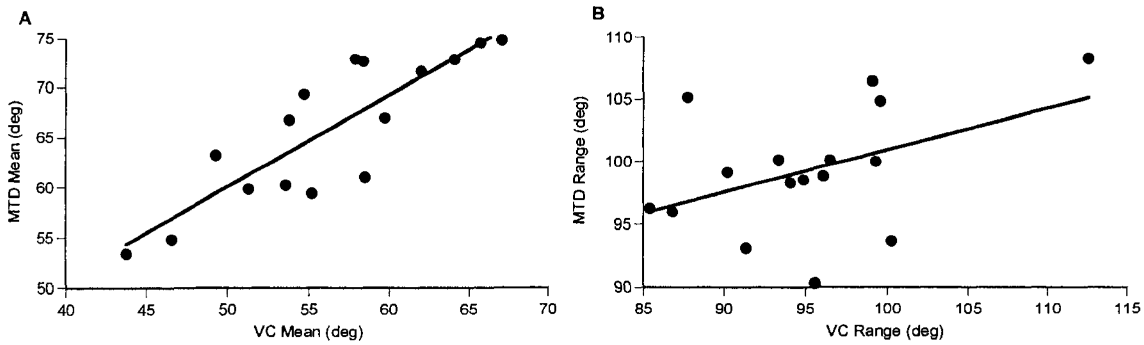


Figure 4.5. Mean (A) and range (B) of humeral elevation angles correlation between the Virtual Corset (VC) and the magnetic tracking device (MTD) in the reach task.

For the flossing tasks, a significant difference was found for the Jerk parameter between the two devices (p = 0.05). The means for the Jerk parameter of the Virtual Corset and the magnetic tracking device were 26% and 22%, respectively, with a moderate correlation (r = 0.46). No interaction was found between the Devices and Position (p = 0.30), however, the main effect was significant for both independent variables, Device (p = 0.001) and Position (p < 0.001). A post hoc paired t-test with Bonferroni correction was conducted for the Device variable. Significant differences were found between the Virtual corset and the magnetic tracking device in % time above 40° (p = 0.005) and % time above 60° (p = 0.001), no significant difference (p = 0.062) were found at % time above 20° (Figure 4.6 – 4.7). High correlations (0.84 – 0.96) were found for all the three Position levels.

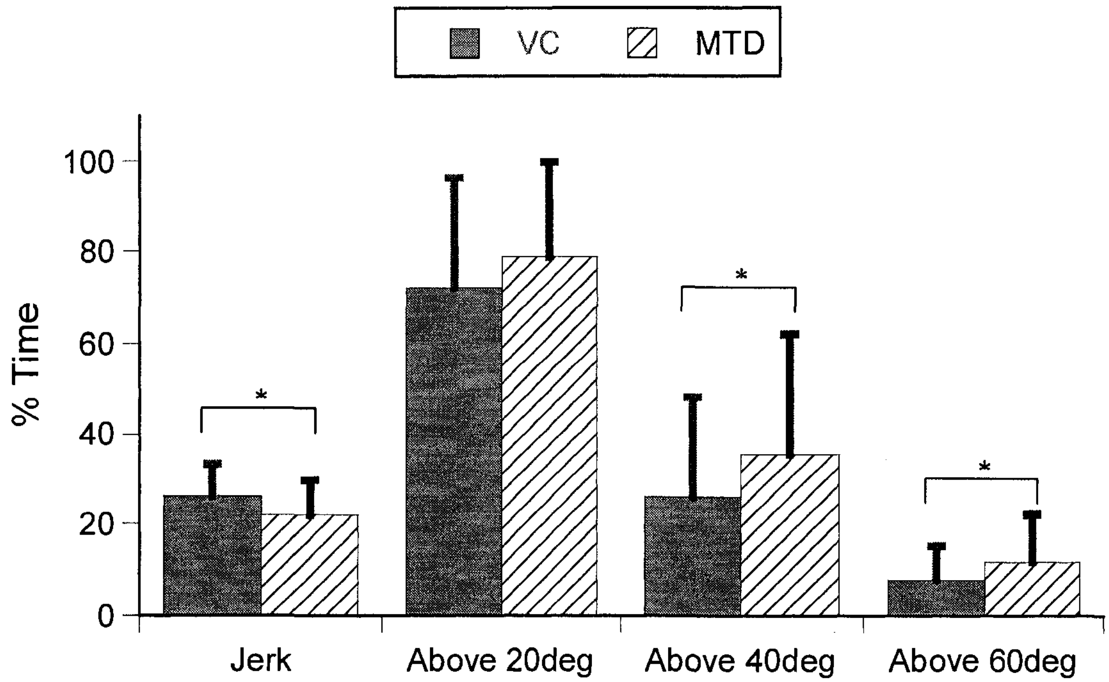


Figure 4.6. Averages of the exposure parameters use to analyze the flossing task.
* $p < 0.05$

DISCUSSION

The Virtual Corset has previously been validated and has shown promising results for the reconstruction of humeral elevation angles. It has been found that the Virtual Corset RMS angle error under static conditions was less than 1° with maximal angle difference error less than 2°. However, under dynamic conditions the size of the error was related to the angular velocity and acceleration and the radius [3]. To the best of our knowledge, the capability of the Virtual Corset to assess humeral elevation angles and identify exposure parameters in-vivo has not previously been evaluated. In the current study, the Virtual Corset was tested under in-vivo dynamic conditions.

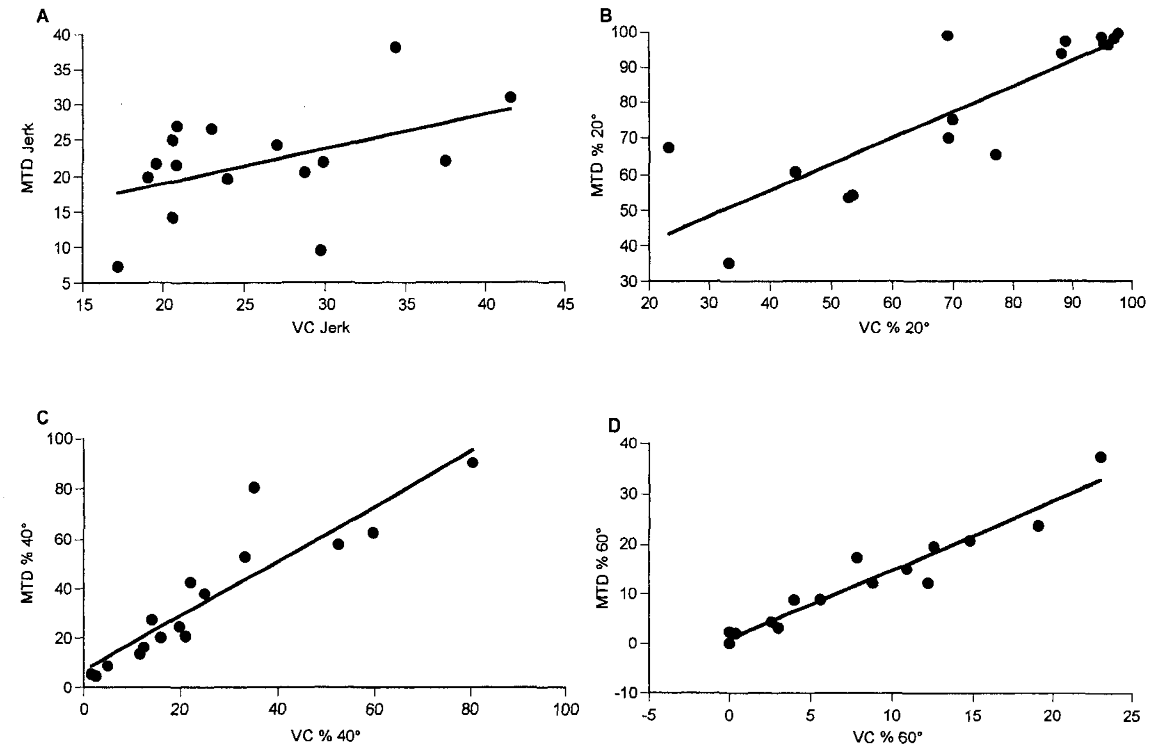


Figure 4.7. Averaged exposure parameters, Jerk (A), %time above 20° (B), %time above 40° (C) and %time above 60° (D), correlation between the Virtual Corset (VC) and the magnetic tracking device (MTD) in the flossing task

Specifically dental hygienists were tested while performing both reaching and flossing tasks with both the Virtual Corset and a magnetic tracking device. The ICCs for the dependent variables used in the study were found to be good to high and the SEMs were low. This indicated a good repeatability for the study dependents variables.

For the reaching task significant differences were found for the mean and range of humeral elevation angles. The average angle differences for the mean and range of humeral elevation were 10° and 4°, respectively. Equation 1, which predicts the Virtual Corset elevation angle error [3], predicted the averaged RMS angle error for the reaching task to be 5.1°. The difference between the Virtual Corset and the magnetic tracking device at the averaged Zero gravity position was 1.6°. At the Zero gravity position, the expectation from the two devices was to read 0° if the humerus was aligned with gravity. However, the Virtual Corset on average read 6.7° and the magnetic tracking device read 8.3°. Both, the magnetic tracking device sensor and the Virtual Corset are surface sensors and one of the main sources of error when using surface sensors methods to measure scapular and humeral kinematics is skin artifact. Ludewig et al.[49] found RMS error of 3.8°, 3.1° and 7.5° for humeral plane of elevation, elevation and external rotation, respectively. The sensor of the magnetic tracking device was located above the epicondyles whereas the Virtual Corset was located close to the deltoid tuberosity, therefore soft tissues artifact might be different between the locations. The Virtual Corset coordinate system is based on the device which would be influenced by subjects' upper arm morphology and the placement of the device. Conversely, the magnetic tracking device coordinate system was based on a humerus anatomical coordinate system which might have been different from the Virtual Corset coordinate system. Another aspect that might have contributed to the differences between the two devices was the maximum RMS error (1.4°) for the magnetic tracking device as a result of the simulated dental hygienist environment. Visualized inspection of the reaching tasks graph for both devices demonstrated similar patterns. For the reaching task, there was a high correlation for the mean humeral elevation angle, which demonstrated that the Virtual Corset pattern was similar to that of the magnetic tracking device. For the range of humeral elevation angles, the correlation was moderate, however the change in the angles were very small relative to the range magnitude.

The primary environment of the Virtual Corset is an occupational setting, measuring and identifying exposure parameters in the workplace during a work day, not specific angle at specific instance in time. In the flossing task, exposure parameters for humeral elevation were examined. The flossing task was performed for a longer time duration (60 seconds) than the reaching task (3 seconds). During flossing, the dental hygienists had to floss between all the teeth, similar to the pattern they use during their work day. The Jerk analysis found significant differences between the two devices. For both devices the Jerk analysis demonstrated that during flossing the dental hygienists are more static/quasi-static than dynamic (more than 70% of the time). For the other exposure parameters (%time above) no interaction between the Device and the Position was found, meaning any differences found between the devices were not related to upper arm position. Main effects were presented for the Device and Position. In this study the Device main effect was of interest, no differences were found in % time above 20° of humeral elevations between the two devices. Significant differences were found for % time above 40° and 60°. However, the variability was large and differences between the means were small (8% and 3%, respectively). The differences in exposure parameters between the two systems might be related to mean angle differences, although the predicted RMS error average for the flossing task was small (1.3°). High correlations were found for the %time above 20°, 40° and 60° which support the hypothesis that the Virtual corset has the ability to identify exposure parameters in the flossing task as well as the magnetic tracking device.

In a study by Bernmark et al. (2002) they have validated a triaxial accelerometer under in-vivo, static and dynamic, conditions by using a three dimensional optoelectronic movement analysis system, Mac Reflex system (Qualisys AB, Sweden) [6]. In the dynamic part of their study subjects performed arm pendulum (flexion/extension) at various velocities for 30 seconds and painting a specific area for the duration of three minutes. Their first dynamic task was similar to our reaching task, although we did not control for arm velocity. They did not report angle differences between the systems, however when examining their graphs similar patterns of the differences between their two systems and ours were identified. In the painting task exposure parameter of % time above bins of 20° was used (from 0° to 180°). A small difference of 2% was identified by them. In this study the differences were slightly higher, 3% - 8%. The reason for the differences could be related to longer duration of data collection time of 3 minutes, whereas, in our study data collection duration for the flossing was on average 1 minute.

Several limitations must be acknowledged. Only reaching task and flossing tasks were used in this study, which might not necessarily represent a complete work day pattern for a dental hygienist. The duration of the two measured tasks were short as a result of a technical limitation of the magnetic tracking device and its interface software, MotionMonitor, collection duration. The Virtual Corset was built to collect data for longer period of time, which might reduce the influence of outliers and as a result would reduce the angle error. Under the current configuration, the Virtual Corset has 5 hours of data collection capacity, which is less than a typical full work day. An increase in the data logger memory size would extend the total data collection time. The use of the Virtual

Corset in the field and data analysis would be easier with a start and end switch on the device. Currently, data collection starts and ends from the moment the battery is placed in or out off the unit.

CONCLUSIONS

The Virtual Corset could identify similar kinematics patterns and exposure data, when compared to a magnetic tracking device. Based on this analysis we believe that the Virtual Corset can be used for data collection in dental hygienist and in other professions that have similar patterns of angular velocity and acceleration and humeral range of elevation as dental hygienist flossing, for example hair dressers. At professions with higher angular velocities and acceleration a prior use of the prediction equation is recommended.

BRIDGE

The third study provided evidence that the Virtual Corset can be used to reconstruct humeral elevation angles well in the reaching task and can identify very well exposure parameters for dental hygienist during flossing. In addition, this study found that it is preferred to use functional tasks to better understand scapular and humeral kinematics in occupational settings. Chapter V describes the differences in humeral and scapular kinematics and humeral elevation exposure during teeth instrumentation on different patients' body types in 16 dental hygienists working in a simulated dental hygiene environment.

CHAPTER V

THE INFLUENCE OF PATIENT'S BODY SIZE ON DENTAL HYGIENIST'S SHOULDER KINEMATICS

In the following study all data collection was performed by me. Dr. Karduna assisted with statistical analysis, interpretation of the results, and manuscript editing.

INTRODUCTION

Shoulder motion has been investigated in many areas and settings including clinical intervention, sports performance, and workplace design. Within workplace design, occupational musculoskeletal disorders have been studied in professions such as mechanics, painters, custodians as well as office, construction, assembly line and dental care workers [14, 19, 21, 24, 32, 57, 70, 75, 76, 89-91, 94, 98, 103, 106].

Proper arm elevation is the result of the interaction between the glenohumeral and scapulothoracic joints. The scapula serves as a stable base for the glenohumeral joint and contributes to arm elevation (scapulohumeral rhythm). Therefore, abnormal position and/or orientation of these bones may interfere with optimal shoulder coordination. Abnormal scapulothoracic joint motion has been found to be associated with pathologies such as idiopathic loss of shoulder range of motion [87], shoulder instability [60] shoulder impingement [53], frozen shoulder [86] and rotator cuff tears [67, 79].

Shoulder pathologies are included under the broad term of musculoskeletal disorders. Musculoskeletal disorders are defined by the United States Department of Labor as an injury or disorder of the muscles, nerves, tendons, joints or, cartilage where the event or exposure leading to the injury or illness is caused by: bending, reaching, twisting, overexertion, or repetition. The outcome of these improper body mechanics can result in sprains, strains, tears, soreness and pain [8]. The United States Department of Labor has reported that in 2005 there were a total of 1.2 million injuries and illnesses requiring days away from work in the private industry. Of those, 30% were due to musculoskeletal injuries. The event that resulted in the longest absences from work was repetitive motion. The injuries that resulted in the longest absences from work involved the shoulder [8].

Studies have shown that dental hygienists suffer from high incidences of musculoskeletal disorders of the neck (37% - 72%) [48, 71], upper extremity (11% - 68%) [1, 48, 71, 110, 111] and back (15% - 65%) [48, 82] and the prevalence of these disorders increases with years of occupation [1, 48, 71, 82]. These pathologies include carpal tunnel syndrome, elbow tendinitis, shoulder impingement and rotator cuff tears. One of the main problems in evaluating the occurrence and prevalence of musculoskeletal disorders in this population is related to the definition of the affected body area. For example, Lidfors et al found that 81% of the dental hygienists in their study reported to suffer from upper extremity disorders. However, Lidfors et al definition for upper extremity included the fingers, hand, wrist, elbow, shoulder and neck [47]. Akesson et al. and Morse et al. have found that the prevalence of shoulder musculoskeletal disorders in this population was as high as, 35% - 68% [1, 71]. Werner et al. found that 13% of the dental hygienist studied suffered from shoulder tendinitis [111]. Liss et al. found that for a given 12 month period, dental hygienist are 2.8 times more likely to report shoulder problems than dental assistants,[48]. Despite these findings research in this area has been insufficient. Most research regarding this population has been based on questionnaire and physician evaluation, which added to the necessity of objective research in this area.

To the best of our knowledge, there has been only one published study which attempted to measure dental hygienist kinematics for the shoulder, however, it was performed in the work place using a video recorder [57]. Markling et al (2005) found that dental hygienists' non-dominant hand was abducted 45% of the time while the dominant hand was abducted 34% of the time. Moreover, shoulders were abducted over 30° of elevation more than 50% of the time, and posture was predominantly static [57]. This study didn't use any markers and was a 2D estimation of back and neck flexion, and humeral abduction. Consequently, the use of a single video camera may have introduced projection errors related to the camera and the dental hygienist positions, which further added to the limitations of this study. There are no reports in the literature on 3D humeral and scapular kinematics of dental hygienists, to the best of our knowledge. There was one study on dentists which measured 3D shoulder kinematics in the work place, without using markers [25].

During a typical work day, dental hygienist work with a wide range of patients, ranging from children to elderly and lean to obese body types. This variety may introduce different difficulties to the dental hygienist. Since the mid-seventies, the prevalence of overweight and obesity has increased sharply for both adults and children in the United States. Data from the Centers for Disease Control and Prevention (CDC) showed that among adults aged 20–74 years the prevalence of obesity increased from 15% in the late seventies to 33% in 2003–2004. There was also an increase in children and teens that were overweight. In 2006, only four states had a prevalence of obesity less than 20% [11]. The increase in population obesity may introduce a more pronounced problem in the near future for the dental hygienists as a result of an increase in obese patients and limitations in dental equipment (such as dental chair and dental stool) as well as working environment size.

Since there are no data on dental hygienists' scapular kinematics and it has been shown in the literature that improper alignment of the humerus and scapula may altered kinematics patterns, and there is only one study [57] which assessed dental hygienists shoulder's exposure, we propose to measure the effects of patient's body type (average chest girth and big chest girth) on humeral and scapular kinematics of dental hygienist during typical dental cleaning work in a simulated workplace environment using a magnetic tracking system. This is a novel model because to the best of our knowledge there is no model designed to measure the influence of body type on dental hygienist scapular and humeral kinematics. This study hypothesized that working on big chest girth patients will result in higher humeral elevation and scapular upward rotation angles in comparison to an averaged chest girth patients.

METHODS

Subjects

Sixteen female dental hygienists average age of 49.6 years (28 – 64 years), height of 166.8 cm (157 – 175 cm) and body mass of 71.1 kg (56.2 – 83.9 kg) participated in the study. Inclusion criteria required that dental hygienists had at least one year of current work experience (actual experience range was 1.5 – 32 years). Exclusion criteria were impairments in arm elevation range of motion (less than 120° of humeral elevation), present injuries to the shoulder or back, any surgery on these body parts in the past two years and any diagnosed neurological disorders. Prior to data collection, all subjects signed an informed consent form approved by the university's Institutional Review Board (IRB).

Instrumentation

To determine whether a patient's body type (big chest girth) creates difficulties for dental hygienists, a questionnaire was conducted on 24 dental hygienists. The dental hygienists had an average work experience of 19 years (2 – 37 years) and at the time of the study were working on average 48 weeks/year (36 – 52 weeks/year). They reported having on average five (1 – 15 patients/week) big chest girth patients per week. The dental hygienists have reported adjusting their body position and their working environment to accommodate for big chest girth patients. In addition, they indicated feeling more stressed at the neck, shoulders and back after treating big chest girth patients (appendix D).

Three dimensional kinematic data from the scapula, humerus and thorax were collected with the Polhemus Liberty magnetic tracking system (Colchester, VT), which consisted of an electronics unit, a transmitter, five sensors and one digitizer. This system was interfaced with the MotionMonitor software program (Innovative sports Training, Chicago, IL). Data were collected at a rate of 120 Hz per sensor. The transmitter emitted an electromagnetic field that was detected by the digitizer and the sensors. The system's electronic unit determined the relative orientation and position of the sensors in space. Data analysis and interpolation were executed using LabView software (National Instruments, Austin, TX).

A simulated work station consisting of a hydraulic dental chair, dental light, and dental hygienist stool was set up in a laboratory setting. Custom made manikins with two body types, big chest girth (big manikin) and averaged chest girth (average manikin), were used to simulate two different patients' body types. Each manikin was fitted with dentures (Dental Hygiene Model: M-YNR-1560, Colombia Dentoform Corp. NY). The manikins were secured to the dental chair using a strap. The big manikin represented the 99 percentile of the American male, with a chest circumference of 138 cm, arm circumference of 46 cm, shoulder width of 66 cm and chest thickness of 35 cm [101, 109]. The average manikin represented the 50% male, a chest circumference of 96 cm, arm circumference of 32 cm, shoulder width of 49 cm and chest thickness of 25 cm [115]. The neck ranges of motion were as followed: extension 18° and 10°, flexion 30° and 6°, and axial rotation 50° and 12° for the average and big manikins, respectively. Mouth opening from lip to lip was 6 cm for the average manikin and 4 cm for the big manikin.

Set-up and Digitization

Five sensors were placed on each subject. A thoracic sensor was attached, using double-sided adhesive tape, to the manubrium just below the jugular notch, then secured in place with adhesive tape. A left and right scapular tracker, previously validated in our lab, were used to quantify scapular kinematics [39]. Plastic screws secured a sensor to the scapular tracker jig. The jig was attached atop the spine of the scapula and acromial process, using adhesive Velcro strips. The humeral sensors were placed on the right and left humerii just above the medial and lateral epicondyles using a customized molded cuff attached by Velcro strips. A global coordinate system was established by mounting the transmitter on a rigid plastic base. The transmitter was located behind the tested subject at the scapular sensors height, at a horizontal distance of 30 cm from the trunk.

The simulated work station was modified to reduce the error by replacing the dental chair's metal head support with wood; also the manikins were made out of fiberglass. Prior to beginning the study, the errors of the magnetic tracking device due to the simulated dental hygienist's work station were assessed. It was found that the highest RMS angle error for the magnetic tracking system at this simulated work station was 1.4°.

During digitization, subjects were in their natural standing position. Anatomical landmarks were digitized for the thorax (T8, xiphoid process, C7 and jugular notch), scapula (root of spine of the scapula, acromial angle and inferior angle) and humerus (medial and lateral epicondyles and ulnar styloid process). The arbitrary axes defined by the magnetic tracking system were converted to anatomically appropriate embedded axes derived from the digitized bony landmarks, based on the ISB recommendation for the upper extremity [116]. All landmarks were surface points and, therefore, could be located directly, except for the center of the humeral head. The center of the humeral head was defined as the point on the humerus that moved the least with respect to the scapula while moving the humerus through short arcs (< 45 degrees) of mid-range glenohumeral motion and was calculated using a least-squares algorithm [104]. After the digitization process, the raw data from the sensors were converted into anatomically defined rotations that could be displayed in real time using the MotionMonitor software. Standard matrix transformation methods were used to determine the rotational matrix of the humerus and scapula with respect to the thorax. For the humerus, the ISB second recommendation was used, taking the ulnar styloid process as the third point for the plane, with the elbow in 90° of flexion [116]. Humeral rotations were represented using a standard Euler angle sequence (Y X' Y") in which the first rotation defined the plane of elevation, the second rotation described the amount of elevation and the last rotation represented the amount of internal/external rotation. Scapular rotations were represented using an Euler angle sequence (Y Z' X") of external/internal rotation, upward/downward rotation, and anterior/posterior tilting.

Experimental Procedure

All testing was completed in a single session. Subjects started the experiment with a shoulder standardized warm-up procedure including Codman's pendulums and stretches for the rotator cuff muscles for both arms [93]. Following the warm-up procedure, subjects removed any object that may interfere with the magnetic tracking system data collection, such as jewelry and belts.

To compare humeral and scapular kinematics while treating patients with the two different body types, dental hygienists had three tasks; instrumenting three different teeth using a universal curette and a mouth mirror (Hu-Friedy, Chicago). The three teeth were numbers 3, 19 and 24 (figure 5.1) for right handed and numbers 14, 30 and 24 for left handed dental hygienists, which correspond to the same teeth positions on the opposite side. For convenience purpose, 3, 19 and 24 will be reported for all data to represent those teeth positions. These specific teeth were based on the simplified oral hygiene index (OHI-S) which contains six teeth as follows 3, 8, 14, 19, 24 and 30. The simplified oral hygiene index is used by dental hygienists to assess oral cleanliness [29].

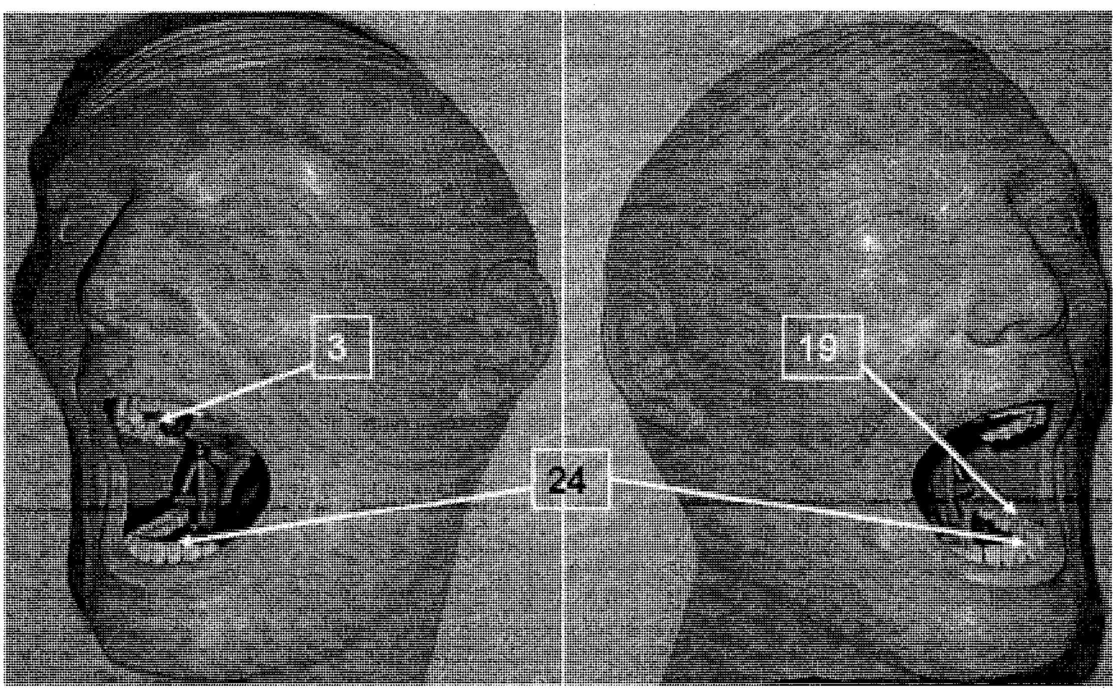


Figure 5.1. Location of the instrumented teeth for a right handed dental hygienist.

The assumption was that these teeth locations would represent different body postures used by dental hygienists to instrument the teeth. Prior to data collection for each tooth, the subjects practiced instrumenting the tooth until they felt comfortable performing the procedure in approximately 30 seconds. Subjects started from a seated position with their arms on the manikin's chest. The dental hygienist was instructed to instrument each tooth for 30 seconds (figure 5.2). Instrumenting a tooth is similar to scaling but without the actual calculus removal. The goal was a representative humeral and scapular motion while working on the entire tooth surface area. At the end of each trial subjects reported if they were able to finish instrumenting the tooth, if not, the trial was repeated. The order of the average and big manikins and the order of the three tasks were randomized. Rest periods of two minutes were given to the subjects between all trials. Each task was repeated twice. The dental hygienists were allowed to adjust the dental stool, dental chair and manikin head position to their preferred position prior to the instrumentation of each tooth. Throughout the entire duration of the study the dental hygienists worked using gloves.

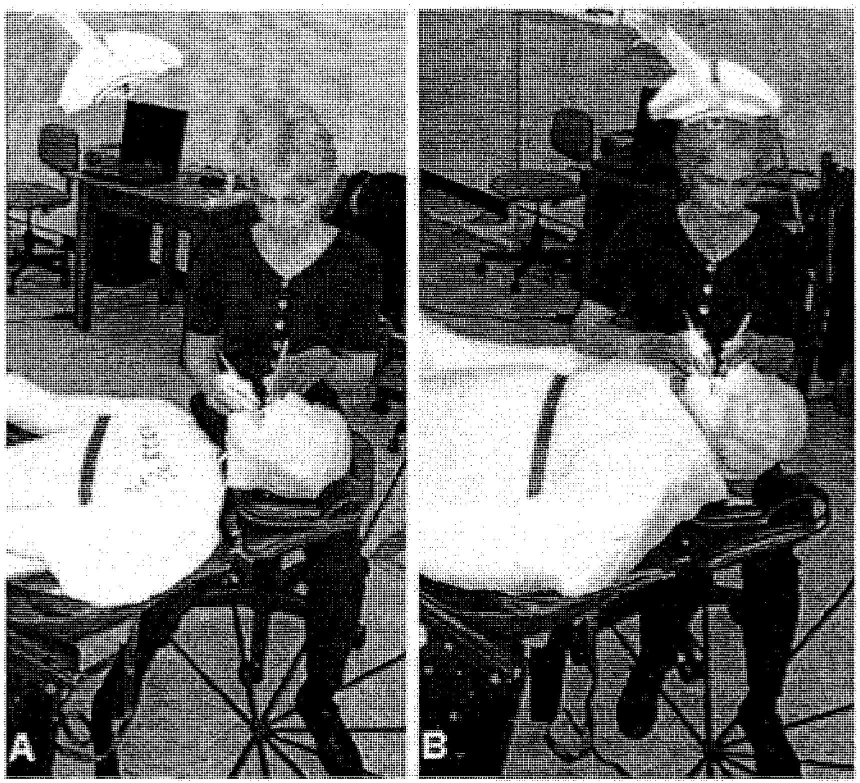


Figure 5.2. Instrumenting the average (A) and the big (B) size manikins

Data Reduction/Statistical Analysis

To quantify differences in humeral and scapular kinematics two independent variables with two levels were chosen Handedness (dominant, or instrumenting hand, and non-dominant hand) and Body Type (average and big manikins). The dependent variables were average humeral plane of elevation, humeral elevation, scapular external rotation, upward rotation and posterior tilt angles. The two trials of each task were averaged and the averaged data of all the three tasks were averaged before performing separate two-way ANOVAs with repeated measures, with average angle as the dependent variable.

Exposure parameters were used to quantify the differences in humeral elevation between two independent variables (Body Type and Handedness) using separate two-way ANOVAs with repeated measures. The chosen exposure parameters were Jerk analysis and percent time above 30° and 60°. The jerk is a parameter describing the repetitiveness of a task and was defined as the percentage of the cycle time spent in time sequences shorter than 1 second within the same exposure bin or 10°. A larger jerk value indicates a more dynamic exposure pattern [58, 70]. The two trials of each dependent variable were averaged for all three tasks, which were averaged for each subject, prior to data analysis. Intra-subject repeatability for all the dependent variables was quantified by intraclass correlation coefficient, ICC (3, 1) and standard error of measurement (SEM).

RESULTS

Intra-subject ICC values for the dependent variables ranged from 0.32 to 0.99 indicating low to high reliability (table 5.1). For the kinematic data the ICC values for all humeral and scapular angles were high and the same was observed for the exposure parameters of percent time above 30° and 60°. For the exposure parameter of Jerk, the ICC values range from low to moderate.

For average humeral elevation angle, a significant interaction between Body Type and Handedness was found ($p = 0.006$). No interaction was found for humeral plane of elevation and scapular angles ($p > 0.12$). However, a significant main effect of Body Type ($p = 0.001$) and handedness ($p = 0.005$) was evident for the humeral plane of elevation and a significant Body Type main effect was observed for scapular upward rotation ($p < 0.001$). Post hoc paired t-tests with Bonferroni correction found significant differences in humeral elevation angles between the average and big manikins for both hands ($p < 0.004$) and between the dominant and non-dominant hands for the big manikin ($p = 0.005$) (figure 5.3 – 5.4).

Table 5.1. Intra-subject reliability of the kinematic and exposure dependent variables for the different orientations scapular external rotation (SER), scapular upward rotation (SUR), scapular posterior tilt (SPT), humeral plane of elevation (HPE) and humeral elevation (HE) for the dominant and non-dominant hand and for the Average and Big manikins.

	Average				Big			
	Non-dominant		Dominant		Non-dominant		Dominant	
	ICC	SEM	ICC	SEM	ICC	SEM	ICC	SEM
SER Average angle	0.99	1.0°	0.93	2.3°	0.99	0.9°	0.99	0.8°
SUR Average angle	0.98	1.4°	0.99	0.8°	0.99	1.0°	0.98	0.9°
SPT Average angle	0.99	1.0°	0.99	1.0°	0.99	1.2°	0.99	0.9°
HPE Average angle	0.89	5.1°	0.95	4.0°	0.95	3.0°	0.98	2.4°
HE Average angle	0.96	1.9°	0.98	1.1°	0.96	2.3°	0.97	1.8°
HE Jerk	0.56	1.8%	0.70	2.0%	0.63	2.0%	0.32	2.1%
HE Above 30	0.95	7.4%	0.91	5.9%	0.96	6.9%	0.93	6.4%
HE Above 60	0.81	3.5%	0.97	2.1%	0.89	4.7%	0.95	3.7%

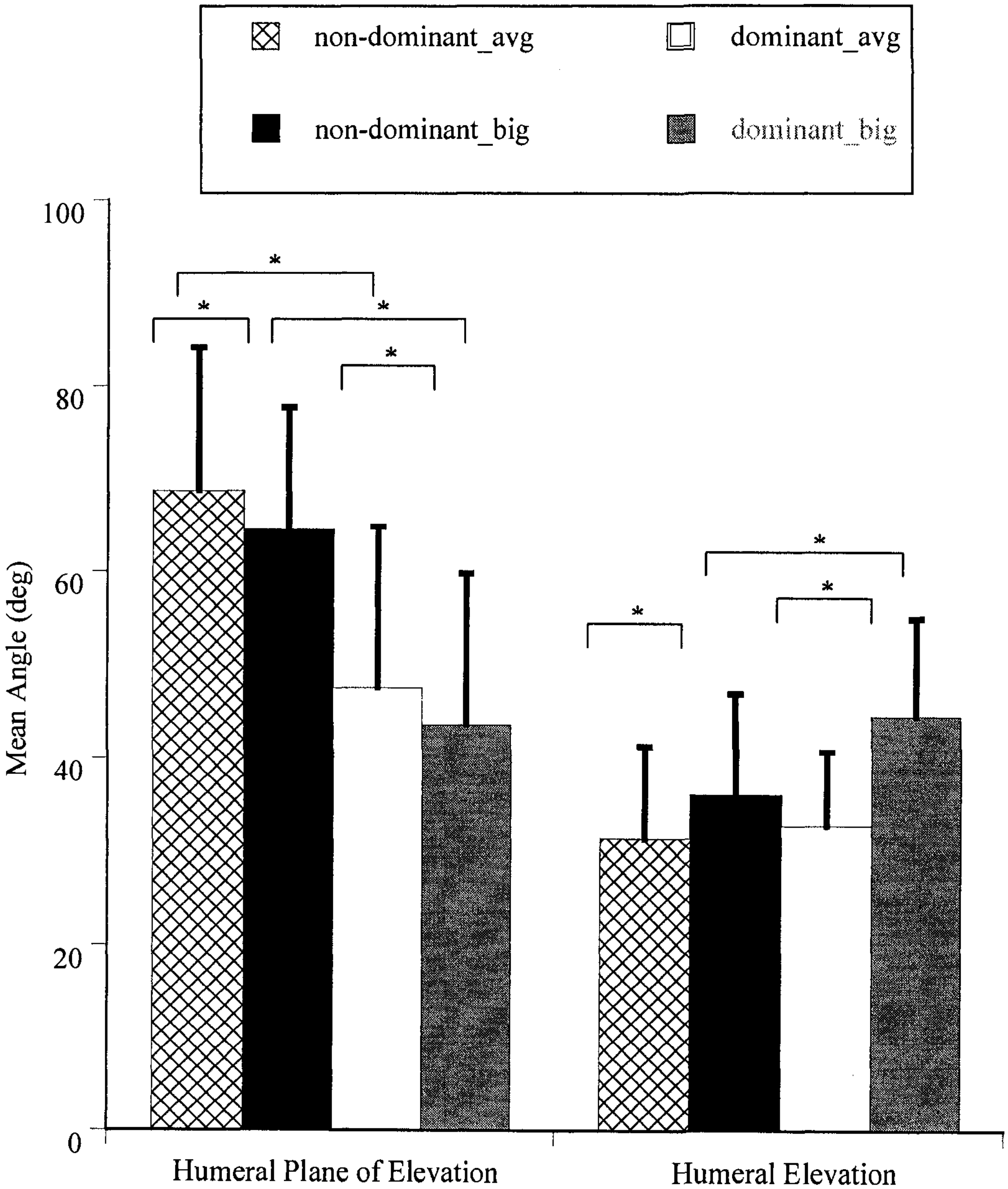


Figure 5.3. Mean and standard deviation of the humeral angles for the non-dominant and dominant hand while working on the two Body Type manikins average and big. * $p < 0.05$

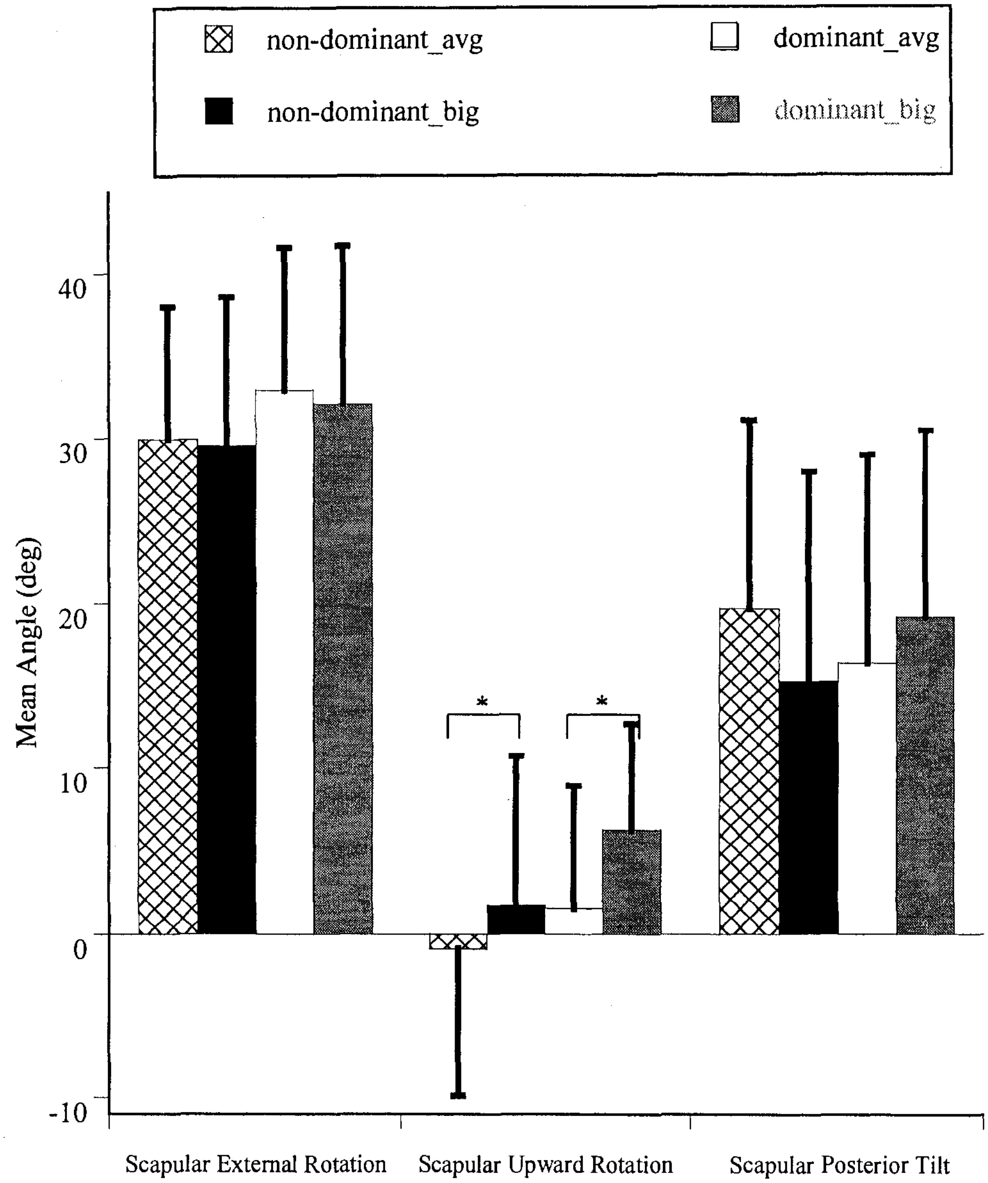


Figure 5.4. Mean and standard deviation of the scapular angles for the non-dominant and dominant hand while working on the two Body Type manikins average and big. * $p < 0.05$

No significant interactions were found between Body Type and Handedness for all exposure parameters data (p > 0.068). Significant main effect differences of Body Type and Handedness were observed for the dependant variables Jerk and percent time above 60° of humeral elevation ($p < 0.013$). The main effect was significant in Body Type for percent time above 30° of humeral elevation ($p < 0.001$). The mean and the standard deviation of the exposure parameters Jerk, percent time above 30° and percent time above 60° were plotted (figure 5.5).

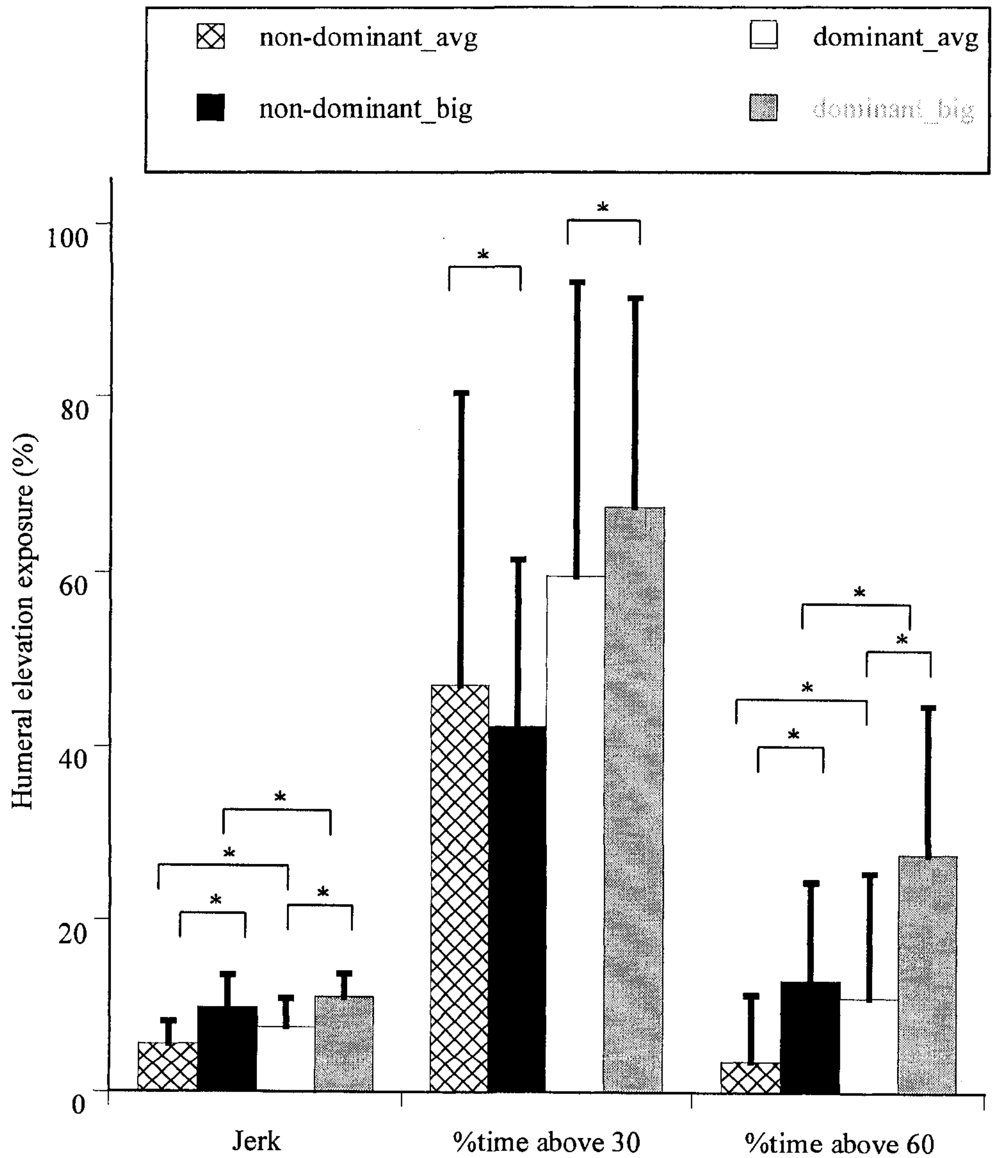


Figure 5.5. Mean and standard deviation of the humeral elevation angles exposure parameters for the non-dominant and dominant hand while working on the two Body Type manikins average and big. * $p < 0.05$

DISCUSSION

Three main risk factors were identified in the literature that contributed to musculoskeletal disorders in the workplace: force (intensity and duration), repetition, and posture (awkward and constrained) [5]. The present study attempted to identify a specific posture risk factor that would alter scapular and humeral kinematics and exposure parameters in dental hygienist. Dental hygienists reported that working on big chest girth patient in comparison to average chest girth patient was more challenging and stressful to their body. Four dependent variables were investigated; the kinematic variable was mean angle for humeral and scapular angles, and the exposure variables were Jerk and percent time above 30° and 60° of humeral elevation. The ICC values for the dependent variables mean angle, percent time above 30° and percent time above 60° were found to be good to high and the SEM values were low. For the Jerk analysis the ICC values were between low to good and the SEM values were low. These demonstrated a good repeatability for the study dependents variables. One explanation to the low reliability values of the Jerk may be related to the short duration of data collection time, each task was performed for 30 seconds. In a typical dental hygienist's work day teeth scaling duration can take 30 minutes or more, per patient, and this pattern is repeated during the work day. The more data collected the smaller the influence of outliers on the dependent variable, Jerk.

The first part of the present study examined the influence of patient's Body Type (big and average) and Handedness (dominant and non-dominant hands) on the mean humeral and scapular angles. Significant interaction was evident between the Body Type and the Handedness variables for mean humeral elevation angle, meaning that the effect of Body Type on mean humeral elevation angle was different for different levels of Handedness. The post hoc paired t-test found significant differences between the big and average manikins for the dominant and non-dominant hands. In both cases the mean humeral elevation angles were significantly larger while working on the big manikin. For the dominant hand the average angle difference was 12° and for the non-dominant hand it was 5°. These differences, below 90° of humeral elevation, contribute to an increase in arm torque, which might increase shoulder muscle fatigue as a result of sustained posture. It was clearly shown that low intensity loading of a muscle in static position for prolonged periods of time could cause muscle damage in animals studies [107]. Sustained static arm position even with low intensity was found to be a risk factor for musculoskeletal disorder in workers [56, 107]. A significant difference was found between the dominant and the non-dominant hands in the big manikin for the mean humeral elevation angle, where the dominant hand was, on average, 9° higher than the non-dominant hand.

No significant interactions were found for the humeral plane of elevation and for all three scapular rotations. Main effects were observed in Body Type and Handedness for humeral plane of elevation and in Body Type for scapular upward rotation. The significant differences between the average and big manikins were about 11° in both hands for humeral plane of elevation. The significant differences, for humeral plane of elevation, between the dominant and non-dominant hands were about 21° in both patients' body types with the non-dominant hand closer to the sagittal plane, whereas the dominant hand was closer to the scapular plane (35° from the frontal plane). For scapular upward rotation, differences were found between the patients' Body Type for both the dominant (5°) and non-dominant (3°) hands with a higher averaged upward rotation angles while working on the big manikin. These differences describe the adjustments in shoulder position dental hygienists have to initiate to accommodate different patient body types. While working on the big manikin dental hygienists plane of elevation angle was always smaller in oppose to working on the average manikin, as a result of patients body size. In order for a dental hygienist to reach their patient's mouth, hygienists have to reach over their patient's chest causing them to elevate their humerus; consequentially, humeral elevation and scapular upward rotation have to adjust when working on larger chest girth patients. The average humeral elevation angles for the dominant and non-dominant hands, for the average manikin, were 33° and 31° and for the big manikin 45° and 36°, respectively. The scapular rotations at neutral position were on average 27° of internal rotation, 4° of downward rotation and 14° of anterior tilt. Comparing these data to neutral position data pulled from a previous study, with the same scapular coordinate system, found on average 30° of internal rotation, 1° of downward rotation and 12° of anterior tilt [2]. Upward rotation elevates the acromion process of the scapula during arm elevation for better clearance of the humeral head to prevent impingement at the lateral edge of the acromial process. Posterior tilt clears the anterior edge of the scapula to prevent impingement at the anterior edge of acromial process, which is a more common site for impingement [26]. The small upward rotation and large anterior tilting might put the dental hygienist at a greater risk for shoulder impingement.

The second part of the study investigated the influence of patient's body type and handedness on humeral elevation angle exposure parameters. No significant interactions were found for all exposure parameters. In the Jerk analysis a significant main effect was found in Body Type and Handedness variables. Differences in Body Type and Handedness were 1% - 2% of time. On average, dental hygienists' posture was found to be more static during teeth instrumentation on the average manikin and for the non-dominant hand. The Jerk analysis, on the instrumentation of teeth 3, 19 and 24, revealed that dental hygienist shoulders were in static posture 90% of the time. The sustained static position might increase shoulder susceptibility to musculoskeletal disorders [56, 107].

A main effect was observed for the exposure parameter percent time above 30° of humeral elevation in Body Type variable. The observed differences were 16% of time for the dominant hand and 13% of time for the non-dominant hand. On average the dental hygienist spent more time above 30° of humeral elevation while instrumenting the big manikin. For the percent time above 60° of humeral elevation, significant main effects were evident in Body Type and Handedness variables. On average, dental hygienist spent more time above 60° of arm elevation while instrumenting the big manikin than the average manikin. The observed differences were 15% and 7% of the time in the dominant and non-dominant hands, respectively. In addition, the dominant hand spent on average more time above 60° of humeral elevation than the non-dominant hand, with observed differences of 9% and 17% time above in the average and big manikins, respectively. During humeral elevation the subacromial space decreases leading to mechanical pressure on the subacromial space soft tissues, which is the largest between 60° and 120°

of humeral elevation [26]. Bernard et al. (1997) defined awkward posture for shoulder musculoskeletal disorders as shoulder elevation above 60°, although, the exposure severity is increasing from 30° of humeral elevation to maximal humeral elevation [5]. With respect to the study, working on a big chest girth patient might increase dental hygienist susceptibility to musculoskeletal disorders as a result of higher humeral elevation angles.

In a simulated environment we are trying to accommodate the benefits of a lab based study and a less controlled but more representative field study. When collecting data in a simulated environment there is always the need to keep the balance between controlled, more precise measurement, and field study which better represents the task, but suffers from lack of control. For instance, using manikins instead of actual patients gave us better control of teeth instrumentation, patients chest girth and neck range of motion between all subjects. However, the manikins did not have all anatomical and physiological variances that one would expect when working on live patients (such as saliva and tongue). One of the repeated comments of the participating dental hygienists in our study was to the fact that obese patients have thicker tongue and cheeks than the averages size patients. This anatomical variance allegedly increases the level of difficulty to instrument the teeth according to dental hygienists in this study. In this study it was impossible to modify the obese manikin to display accurate anatomical variances due to a lack of anthropometric data in literature regarding the obese population's tongue and cheek thicknesses. However, we believed that chest size and neck range of motion would identify differences in shoulder kinematics. In the current study we chose to instrument each tooth in 30 seconds to quantify the differences between Body Type and Handedness. The reasoning for that was based on the magnetic tracking device and the interfacing MotionMonitor software data collection duration ability. Another limiting factor was the wide range of dental hygienist work experience and age variations. The large varieties in dental hygienist height and weight also have influenced the way the dental hygienist approached the two manikins. It is possible that tall dental hygienist may have less difficulty when working with obese patients while still seated than shorter dental hygienists. Another limitation observed was that each dental hygienist had a unique way to approach and instrument each manikin. Furthermore, the dental hygienists altered their working patterns based on their need and the patient's need (treating the manikin like a traditional patient). For example while working on the big manikin two dental hygienists stood during instrumentation in order to reduce their humeral elevation angles.

CONCLUSIONS

The study findings supported dental hygienists' claim of difficulties and body stress while working on big chest girth patients. It was found that dental hygienist, on average, sustained higher humeral elevation angles while instrumenting the big manikin. Patients of greater girth may increase dental hygienist susceptibility to shoulder musculoskeletal disorders. Although in the present study dental hygienist instrumented only three teeth, it is believed that these teeth covered a representative range of shoulder motion of the dental hygienist. We believe that a similar shoulder motion patterns would be seen during instrumentation of other teeth. Based on the present study results dental hygienist should be more aware of their body posture specifically shoulder position while working on big chest girth patients. Ergonomic interventions may be needed to facilitate solutions to problems associated with treating these patients. Finally, we believe that fitness programs design to strengthen scapular stabilizing muscles will be beneficial to the dental hygienist. The program goal will be to increase dental hygienist ability to stabilize their scapulae and increase scapular neutral upward rotation and decrease anterior tilt, which may lead to a decrease in the prevalence of shoulder musculoskeletal disorders.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Musculoskeletal disorders are one of the main areas investigated in occupational settings. Three major risk factors were identified in the workplace related to musculoskeletal disorders force, repetition and posture. Awkwardly constrained posture sustained for a long period of time was found to increase the likelihood of developing musculoskeletal disorders. It has been shown that arm elevation above 60° or 90° can increase the susceptibility for shoulder injury, if chronically exposed throughout a work day. To measure the exposure to these risk factors three methods are commonly used questionnaire, observation and direct measurement. The first two methods are subjective and not precise whereas, the direct measurements are objective and accurate. Sophisticated kinematic equipment is expensive, hard to operate, takes a long time to process and analyze the data, and has a limited data collection capacity. An ambulatory device that can precisely identify the worker's shoulder posture and repetitiveness was needed for this type of study. The Virtual Corset is a, low cost commercially available, triaxial accelerometer device that can fulfill this purpose.

Although exposure of arm elevation during a work day is important, it might not be sufficient to identify a specific repeated event during a day of work that may contribute to upper extremity musculoskeletal disorders. Dental hygienists are in an occupational group identified as one that suffers from musculoskeletal disorders of the upper extremity, with the prevalence of the injury increasing with time. Dental hygienists have identified the work on big girth chest patients as a contributor to upper extremity fatigue and stress. This study also addressed the issue of identifying a specific factor that may contribute to shoulder stress, which may lead to shoulder injuries.

The purpose of this dissertation was twofold the first one was to validate the Virtual Corset to measure upper extremity exposure parameters in an occupational setting. The second one was to learn if humeral and scapular kinematics altered as a result of patient's body type.

The first study characterized the differences and variability in scapular kinematics in healthy adults during constrained and unconstrained (functional) humeral elevation tasks. Constrained protocols are more frequently used in shoulder research. Differences in scapular kinematics were found between constrained and functional humeral elevation tasks, at the same humeral plane of elevation and elevation. Furthermore, the between subject variability was the same for the constrained and overhead functional tasks. The largest differences were observed in scapular upward rotations. Tasks that involved small humeral elevation and/or involved trunk flexion had higher angle differences relative to the task's range of motion. This may lead to the first conclusion that caution needs to be taken when comparing, generalizing, and normalizing scapular kinematic data drawn from constrained humeral movements and applying it on functional humeral movement, in healthy populations. Second, based on the results from this study it seems that it is not always necessary to use constrained humeral elevation in the scapular plane to measure scapular behavior.

The second study involved validating the use of a triaxial accelerometer for the reconstruction of humeral elevation angles under static and dynamic conditions. Under static conditions the Virtual Corset accuracy was very good. However under dynamic conditions the accuracy of the Virtual Corset was related to the magnitude of the angular velocity and acceleration and the radius. It was concluded that the Virtual Corset can predict elevation angles well under static and quasi-static conditions. The prediction equation is recommended, which predicts elevation angle error, to quantify angle error magnitude for a specific occupation prior to data collection. Also, to reduce the predicted angle error distance of the Virtual Corset from the axis of rotation should be minimized.

The purpose of the third study was to validate in-vivo the ability of the Virtual Corset, to reconstruct humeral elevation angles, and identify humeral elevation exposure parameters in an occupational group. Its ability was measured in dental hygienists in simulated environment using a magnetic tracking device. It was evident in the reaching tasks that the Virtual Corset can identify the patterns of the motion. During the flossing task the Virtual Corset was also able to identify the exposure parameters. While performing the flossing technique the dental hygienists' humeral motion was found to be more static than dynamic. It was concluded that the Virtual Corset can be used for data collection of kinematics and exposure parameters in occupational groups with similar dynamic patterns as dental hygienists during the reaching and flossing tasks.

The purpose of the fourth study was to try and identify a specific work related risk factors which may contribute to shoulder musculoskeletal disorders in dental hygienists. The specific risk factor that was identified by dental hygienists was working on a big chest girth patients. Differences between two body types (big and average) in shoulder kinematic and exposure were found in the dental hygienist group while instrumenting three specific teeth (3, 19 and 24). Main differences were observed in scapular upward rotation and humeral elevation angles, on averaged dental hygienist angles were higher while instrumenting the big manikin. We concluded that dental hygienists altered their kinematic pattern of the shoulder to accommodate for the big chest girth patients while instrumenting their teeth. It was also found that during instrumentation of the teeth dental hygienist are predominantly in a static posture, over 90% of the time.

The findings of this dissertation may contribute to the understanding of musculoskeletal disorders from two different aspects. The first aspect was related to the ability to measure shoulder exposure data in the workplace. This study offers improved perceptive of accelerometers and their use in field studies as inclinometers. We gained a better understanding of the capabilities and limitations of the triaxial accelerometer. These insights may facilitate the collection of more statistically relevant exposure data in the workplace, and facilitating data reduction and analysis to be easier and faster. The ability to predict the Virtual Corset angle error prior to data collection in a selected occupational environment strengthens the validity of the data collected. In addition, it may also save time and money by avoiding the use of the triaxial accelerometers for data collection in inappropriate occupational settings.

The second aspect of the dissertation addressed the differences between constrained and functional humeral elevation protocols and the ability to identify a specific risk factor for shoulder musculoskeletal disorders in a specific occupational group, dental hygienists. The results of the study highlighted the differences in scapular kinematics in constrained and functional protocols. This may help researchers and clinicians to create a battery of tests for better assessment of shoulder kinematical patterns, similar to gait analysis used to assess lower extremity function. Moreover, it was found that dental hygienist shoulder kinematic patterns were different based on the patient's body type. This finding may lead clinicians, researchers, and ergonomists to intervene in this area and to improve dental hygienist environment to accommodate for different body types of patients; which may reduce susceptibility and prevalence for musculoskeletal disorders.

STRENGTH OF THE STUDY

This research has several strengths. First, in this study we have compared scapular kinematics at the same humeral elevation and plane of elevation between constrained tasks and functional tasks, in a wide range of humeral elevations and planes of elevation. In the literature most of the studies related to scapular kinematics used constrained protocols. Fewer used functional protocols to investigate scapular kinematics; however, no study compared the two protocols at the same humeral elevation and plane of elevation.

Second, constrained humeral elevation in the scapular plane is the most common protocol used to examine scapular kinematics. The assumption is that elevation in the scapular plane is more natural and will have less variability between subjects. We hypothesized that functional overhead protocols are more frequently used by the subjects, on daily basis, which will lead to a similar between subject variability as in the constrained humeral elevation in the scapular plane. This comparison had not been done previously.

Third, for exposure measurement there are no commercially available triaxial accelerometers with built in data logger besides the Virtual Corset. We were able to validate the Virtual Corset under static and dynamic conditions; which simulated humeral elevation angle in different planes of elevation. The wide range of static positions and the use of pendulum with a wide range of angular velocities, and accelerations at different plane of elevations created a closer simulation to humeral elevation.

Fourth, in the literature it is always indicated that the use of accelerometers to measure exposure is limited by linear acceleration introduced to the system. Therefore, the literature suggests using accelerometer in occupations that are static or quasi-static in nature. However, no range of angular velocities and accelerations is offered. In this study we offer a prediction equation to predict the accelerometer elevation angle error based on angular velocity and acceleration, radius, and elevation angle. This equation can be used prior to data collection to identify the practicality of the accelerometer to measure exposure data in a specific occupation.

Fifth, in the third study the Virtual Corset was validated in-vivo in a dental hygienist group during reaching and flossing tasks in a simulated environment. The validation was with respect to the humeral anatomical coordinate system, which better represent humeral kinematics during different activities. In the literature the validation of the accelerometer is reported with respect to a surface based coordinate system and not anatomical based coordinate system.

Finally, the fourth study was the first study to address 3D humeral and scapular kinematics. It was also the first study to address patient's body type as a risk factor for dental hygienist's shoulder musculoskeletal disorders.

LIMITATIONS OF THE STUDY

In the first study two main limitations were identified. First, subjects performed each task once to avoid fatigue, thus subject reliability testing could not been performed. Scapular kinematics has been found to be reliable under constrained protocols in the frontal, scapular and sagittal planes. In our study we have covered larger range of humeral planes of elevation. To the best of our knowledge, no reliability tests have been reported for scapular kinematics while performing functional shoulder protocols. However, the functional movements such as the ones in the present study are used more frequently in daily activities than constrained motion. Second, pilot data collection revealed that subjects had altered the way they reached to the different functional targets when the constrained tasks were introduced first. Not randomizing the order between the constrained and functional protocols may have introduced an error related to fatigue or sensor slip. To minimize fatigue, subjects had three minutes of rest between trials and the functional testing consisted of only six arm motions. This method has been extensively used in our laboratory and has demonstrated good reliability.

In the second study the main limitation was related to the dynamic condition used to validate the Virtual Corset. Although, the pendulum setting for the dynamic condition represented a wide range of angular velocities and accelerations it represented only one possible pattern with respect to gravity. Also, in this pattern more data points were concentrated at the end range of motion (angular velocity was low) and the data points were more spread in the mid-range of motion (angular velocity was high).

In the third study the main limitation was relatively short time period of data collection, less than two minutes. The reason for this limitation is technical and related to the magnetic tracking device and its interface program the Motion Monitor. Longer time period of data collection would probably reduce the error and differences found between the two devices, and better simulate patterns seen in specific occupation.

In the fourth study the main limitation was the variability between the subjects performing the task. The participating dental hygienists portrayed a wide range of work experience, age differences, height and weight which influenced the way the dental hygienist approached the two manikins. Each dental hygienist had her own unique way to approach and instrument a patient. Furthermore, the dental hygienists change their working patterns based on their need and the patient's need. However, this gave us a better representation of dental hygienist work.

RECOMMENDATIONS FOR FUTURE RESEARCH

As mentioned before, constrained humeral elevation protocols are commonly used to study scapular kinematic. However, constrained arm motions are not commonly used in our daily routine, such as activity of daily living and work related activities. Our first study has found differences in scapular orientations between constrained and functional tasks. It also found that the between subject variability was good for overhead tasks. Future research in this area needs to concentrate on determining the reliability of different functional shoulder activities in different humeral elevations and planes of elevation angles and at different velocities. A test that can evaluate shoulder motion, similar to the function of gait analysis in lower extremity, should be developed and validated. The test should consist of a variety of functional tasks performed continuously and in a cyclic manner.

With respect to the Virtual Corset, field studies on different occupations should take place. These occupations could be dental hygienists, dental assistants, hair dressers, masons, mason tenders and office workers. We could use the device to learn about these occupations' daily routine and quantify the exposure related to shoulder musculoskeletal disorders risk factors. The Virtual Corset can also be used to compare people's range of motion and activity levels before and after an intervention, such as rehabilitation, surgery and fitness program. Moreover, the use of the Virtual Corset to measure lower extremity and trunk exposure data need to be investigated.

With respect to dental hygienists' humeral and scapular kinematics more research is needed. The influence of patient's body type on dental hygienist shoulder kinematics while instrumenting different teeth and/or flossing needs to be further investigated. Also, the psychological effect of patient's body size on the dental hygienist is needed to be investigated. The influence of different intervention programs (ergonomic or fitness program) on dental hygienists susceptibility for shoulder musculoskeletal disorders needs to be measured. Some of the tools that can be used as an ergonomic intervention could be as simple as educating and increasing dental hygienist awareness to their shoulder position while working on big chest girth patients.

APPENDIX A

CONSENT FORM STUDY 1

University of Oregon

Consent to Take Part in a Research Study

Project: Scapular Kinematics in Constrain and Unconstrained Upper Extremity Movement

You are invited to participate in a research study conducted by Andrew Karduna, PhD, from the department of Human Physiology at the University of Oregon. The purpose of this investigation is to study the kinematics (movement) of the scapula under constrain and unconstrained arm movements. You were selected as a possible participant in this study because you have no history of shoulder pathology.

If you decide to participate, you understand that the following things will be done to you. You will be asked to fill out a brief form to provide basic information such as age, height and weight and which arm is your dominant arm. Non-invasive measurements will be made throughout the experiment. To perform these measurements, small sensors will be attached by straps or tape to your hand, forearm, arm, sternum scapula and head. You will be asked to actively move your arm in different planes of motion. You will be then asked to perform few daily functional movements. The entire testing process should take about 90 minutes.

There is no direct benefit to you by participating in this study. However, you understand that information gained in this study may lend to a better scientific understanding of how the position of the shoulder joint is perceived in unconstrained tasks. You will be paid \$20 for your participation in this study. This is to help defray the costs incurred for participation such as transportation as well as your time. If you cannot complete the study, you will still be paid \$10 for your time.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Subject identities will be kept confidential by coding the data with subject numbers, rather than names.

Your participation is voluntary. Your decision whether or not to participate will not affect your relationship with the University of Oregon. If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty.

If you have any questions, please feel free to contact Dr Andrew Karduna, (541) 346-0438, Department of Exercise and Movement Science, University of Oregon, Eugene OR, 97403. If you have questions regarding your rights as a research subject, contact the Office of Human Subjects Compliance, University of Oregon, Eugene, OR 97403, (541) 346-2510. You have been offered a copy of this form to keep.

Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you have received a copy of this form, and that you are not waiving any legal claims, rights or remedies.

Print Name____

Signature____

Date____________________

APPENDIX B

CONSENT FORM STUDY 3 & 4

University of Oregon
Consent to Take Part in a Research Study
Project: Unconstrained Arm Kinematics and Exposure in Dental Hygienist

You are invited to participate in a research study conducted by Andrew Karduna, PhD, from the department of Human Physiology at the University of Oregon. The purpose of this investigation is to validate a device (Virtual Corset) to measure arm motion in dental hygienists and to study the motion of the arm and shoulder blade while treating a big chest girth patient relative to average chest girth patient. You were selected to participate because you are a practicing dental hygienist.

If you decide to participate, you understand that the following things will be done to you. You will be asked to fill out a brief form to provide basic information such as age, height and weight and which arm is your dominant arm, as well as your health and working conditions. Non-invasive measurements will be made throughout the experiment. To perform these measurements, small sensors will be attached by straps or tape to both of your arms and shoulder blade and one on the sternum. Also a small, pager size sensor will be attached to your arm with a neoprene arm band. You will be asked to actively move your arm and reach to a specific target and pick up an object. You will then be asked also to perform few of your daily routine tasks, such as probing and scaling, while working on simulated patients. The entire testing process should take about 90 minutes.

There is no direct benefit to you by participating in this study. However, you understand that information gained in this study may lend to a better scientific understanding of how to develop ergonomics intervention in the dental hygienist work environment to reduce risk for musculoskeletal disorders. You will be paid $50 for your participation in this study. This is to help defray the costs incurred for participation such as transportation as well as your time. If you cannot complete the study, you will still be paid $15 for your time.

Photography and videotaping will help with our understanding of your work pattern relative to the patient. If you agree to be photographed or videotaped, please mark the yes option. This answer will not interfere with your participation or compensation for this study.

Yes_____ No______
If you choose yes, please read and sign the agreement for photography and videotaping form.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Subject identities will be kept confidential by coding the data with subject numbers, rather than names.

Your participation is voluntary. Your decision whether or not to participate will not affect your relationship with the University of Oregon. If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty.

If you have any questions, please feel free to contact Dr Andrew Karduna, (541) 346-0438, Department of Human Physiology, University of Oregon, Eugene OR, 97403. If you have questions regarding your rights as a research subject, contact the Office of Human Subjects Compliance, University of Oregon, Eugene, OR 97403, (541) 346-2510. You have been offered a copy of this form to keep.

Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you have received a copy of this form, and that you are not waiving any legal claims, rights or remedies.

Print Name____

Signature____

Date________________________

Agreement for Photography and Videotaping

I have received an adequate description of the purpose and procedures for any photography and/or videotaping that may utilized during the course of the proposed research study. I give my consent to allow myself to be captured on film and/or videotaping during participation in the study, and for those images to be viewed by persons involved in the study, as well as for other professional purposes, including conference presentation and scientific publication of findings from the study, as described to me. I understand that all the information will be kept confidential and will be reported in an anonymous fashion, and that the films will be erased after an appropriate period of time after the completion of the study. I further understand that I may withdraw my consent at any time.

Print Name ____

Signature of Participant ____________________________________

Date ____________________

Please place your initials in the fields below indicating your willingness to have your images used in the following circumstances:

i. For the current study only __________

ii. For future studies attempting to further research knowledge __________

iii. For training professionals and graduate students __________

iv. For lectures, publications, and professional conferences __________

APPENDIX C

DENTAL HYGIENIST QUESTIONNAIRE

Dental hygienist Questionnaire

You are invited to participate in a research project on the differences in dental hygienist work while working with patients with a big chest girth relative to an average chest girth. The project is being conducted by Dr. Andy Karduna, from the Department of Human Physiology at the University of Oregon. The research will help us better understand the risk factors of a dental hygienist's working environment and patient type. This information may help us improve working environments in the future, and increase awareness of potential risk factors.

All you need to do is complete this short questionnaire, which should take approximately 10 minutes. Your participation is voluntary. If you do not wish to participate, simply discard the questionnaire. Responses will be completely anonymous; your name will not appear anywhere on the survey. Completing and returning the questionnaire constitutes your consent to participate.

Keep this letter for your records. If you have any questions regarding the research, contact Dr. Andy Karduna, (541) 346-0438 or karduna@uoregon.edu. If you have any questions regarding your rights as a research subject, please contact the Office for Protection of Human Subjects at the University of Oregon, (541) 346-2510. This Office oversees the review of the research to protect your rights and is not involved with this study.

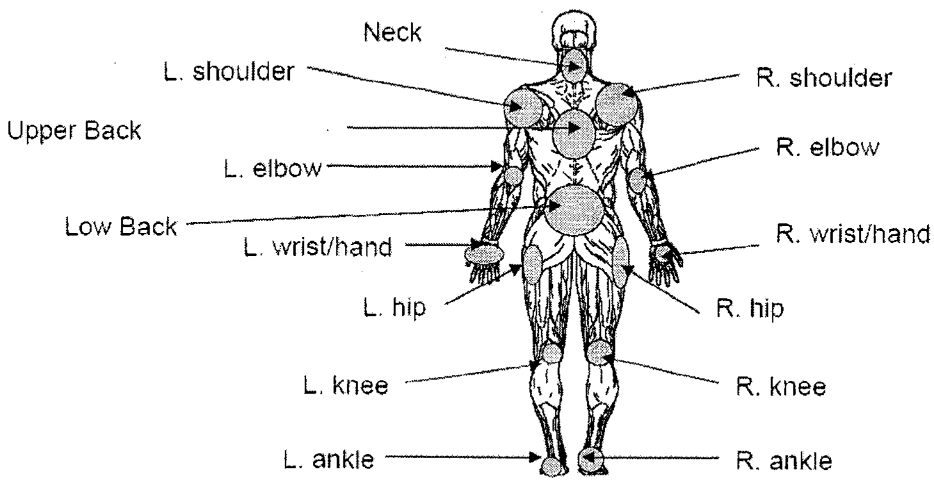
Thank you again for your help.

Section 1: Tell us about your work

1. Number of years working as a dental hygienist? ___________years.
2. On average how many
   a. Weeks per year do you work?___________Weeks/year.
   b. Days per week do you work?___________Days/week.
   c. Hours per day do you work? ___________Hours/day.
3. Are you ❑ left or ❑ right handed? (check one)
4. Type of patients you typically work with? (check all that apply)
   ❑ Big chest girth/obese ❑ Elderly (over 65 yrs) ❑ Kids (10 yrs and under) ❑ None of these

Section 2: The reminders of the question are related to big girth patients. If you do not work with this type of patients, stop here.

5. Approximately how many of these patients do you treat in a week?
   ___________Big girth patients/week.
6. Are there any differences when working with this type of patients relative to the average size patients?
   ❑ Yes ❑ No
   Please describe the differences ____.
   ____.
7. Is your working position different while working on this type of patients relative to the average size patient?
   ❑ Yes ❑ No
8. How does your body feel after the treating this type of patients relative to the average patient?
   ❑ More stressed ❑ The same ❑ Less stressed
9. If more stressed, in which area of your body do you feel the stress? Circle all that apply.



10. While working with this population, what is your body posture?
    a. Right elbows: ❑ More raised to the front ❑ More raised to the side ❑ The same
    b. Left elbows: ❑ More raised to the front ❑ More raised to the side ❑ The same
    c. The back: ❑ More bending forward ❑ More bending to the side ❑ More twisted ❑ The same
    d. The neck: ❑ More flexed forward ❑ More bending to the side ❑ More twisted ❑ The same
11. Do you adjust your work environment differently for this type of patients:
    a. Stool height adjustment: ❑ Higher ❑ The same ❑ Lower
    b. Dental chair Adjustment
        i. Overall chair height: ❑ Higher ❑ The same ❑ Lower
        ii. Head rest: ❑ Higher ❑ The same ❑ Lower
        iii. Back rest: ❑ Higher ❑ The same ❑ Lower
        iv. Legs rest: ❑ Higher ❑ The same ❑ Lower
12. Do you feel the arrangement of your work environment is appropriate to work with this type of patients?

    ❑ Yes ❑ No

    a. If no, where are the problems? ❑ Dental stool ❑ Dental chair ❑ Room size
    b. Please describe:____.

    ____.

    ____.

13. Do you have any other concerns you want to add regarding the differences in working on big girth/obese patients than on the average size patients that you want to add:

Thanks for your help.

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