Shoulder Joint and Muscle Exposure in Violin Musicians:

A Three-Dimensional Kinematic and Electromyographic Exposure Variation Analysis

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DEDICATION

This dissertation is dedicated to my family:

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ABSTRACT

Subacromial impingement syndrome is a common disorder in the right shoulders of orchestral violinists. Studies performed to date on this population have been limited in terms of kinematic methods used, resulting in inability to relate recorded motions to clinically relevant motions. They have also used temporal EMG analysis, which can be misleading in terms of exposure. Previous kinematic research on non-musician populations, and using non-occupational tasks, have indicated that subacromial impingement is associated with reduced posterior tilting and upward rotation of the scapula, as well as increased upper trapezius and decreased serratus anterior activation.

This study compared 20 violinists (3 males and 17 females) with right sided SIS to 30 normal controls (11 males and 19 females) in the performance of 30-second, randomized performances of slow and fast standardized musical repertoire (each score being played 4 times). Surface EMG of upper trapezius and serratus anterior were sampled at 1,000 Hz using pre-amplified electrodes and signals were further amplified and RMS processed at 100 ms to improve signal to noise ratio. Signals were normalized to resting EMG and relative voluntary electrical activity (RVE). Three-dimensional kinematic data were captured in a standardized fashion by mathematically embedding local coordinate systems within the trunk, scapula and humerus, and rotations of these segments about the embedded axes were sampled at 100 Hz. EMG and 3-D kinematic data were then analyzed using Exposure Variation Analysis (EVA) methods, which expresses 3 amplitudes of the EMG or kinematic signal in terms of time spent at each amplitude level. EVA arrays were expressed in 3X3 graphs and were analyzed in terms of speed effects (fast and slow), and injury effects (injured and uninjured) using Mixed-Effects Multinomial Logistic Regression statistical methods. The reliability of the EVA method was evaluated by calculating intraclass correlation coefficients (ICC) and standard error of the measurement (SEM) statistics for all EVA cells and for all dependent variables.

The EVA methods used in this study were found to have moderate to high levels of reliability (moderate to high ICC and low SEM). The EVA method was able to discern differences in terms of speed and injury in both injured and uninjured participants. Musicians in both groups were observed to play in positions of increased glenohumeral internal rotation compared to non-musician subjects participating in other research studies at similar humeral elevation angles. Injured musicians were noted to play in positions characterized by increased posterior scapular tilting for longer durations of time, increased scapular upward rotation for longer durations of time, and increased scapular internal rotation at slow speeds. Injured musicians were also noted to adopt positions of increased scapular posterior tilting, increased scapular upward rotation for longer durations of time, and increased scapular internal rotation at fast speeds. When compared to their uninjured counterparts, injured musicians were also noted to perform with reduced amplitude but more static (longer duration) glenohumeral flexion, as well as with slightly increased glenohumeral external rotation compared to uninjured musicians. Injured musicians were noted to perform with increased short duration, low amplitude upper trapezius activity at slow speeds, while they played with reduced long duration, high amplitude recruitment at fast speeds. Lastly, injured musicians were noted to demonstrate increased amplitude of recruitment of serratus anterior at both slow and fast speeds.

The EVA method of data reduction employed in this study was instrumental in identifying these differences where more traditional methods (also attempted in this study) failed to identify group differences with respect to injury. This study has therefore identified a reliable kinematic and EMG data reduction technique that can be used to assess the kinematics of shoulder motion, as well as the upper trapezius and serratus anterior muscle activation in violin musicians.

The findings of this study suggest that violinists develop SIS because of the positions they adopt in playing the violin, and that the injured musicians may have developed compensatory strategies to avoid discomfort.

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CHAPTER 1

INTRODUCTION

Purpose

The primary purpose of this study was to determine the relationship between presence or absence of right-sided shoulder impingement syndrome (SIS) in violinists, and right shoulder kinematic and electromyographic (EMG) exposure variation analysis (KEVA and EEVA) patterns.

Several studies have been published that describe three-dimensional kinematic, and EMG factors that have been shown to be associated with SIS. However, no studies have been performed that support these kinematic and EMG associations with SIS in musicians, and those that have attempted to identify the association between kinematic variables and SIS have not been truly three-dimensional, making the association sub-optimal. Exposure variation analysis (EVA) has been proposed as a superior data reduction technique to temporal analysis (Mathiassen and Winkel, 1991) when assessing workers' simultaneous exposure to adverse kinematic and/or EMG magnitude, and repetition, but this technique has not been used to evaluate musicians' exposure to injury-related factors.

The quantitative assessment of KEVA and EEVA in relation to different performance characteristics (performance of repertoire at different speeds) is expected to contribute to furthering understanding three-dimensional shoulder kinematic, and upper trapezius and serratus anterior muscle exposure during musical performance. Secondly, this quantitative assessment was intended to provide a baseline comparison for future research into therapeutic interventions aimed at the abatement of these exposures. Lastly, it was anticipated that this information would be used to develop a valid and reliable tool that could be used to quantify kinematic and muscle exposures in musicians who play other musical instruments.

The effects of other outcome variables, such as instrument dimensions, anthropometric dimensions, and physical examination outcomes, on these kinematic and electromyographic variables were assessed with respect to their relationship to SIS.

Background

After completing an extensive literature review, it was found that methods cited to measure exposure to harmful workplace factors are either unrelated to the violinist population, or are lacking in objective methodology to ensure accuracy, or have little relevance to actual performance limiting factors. For example, from a historical perspective, “exposure” as it relates to injured workers, refers to the average exposure to harmful agents such as radiation (Hägg et al, 2000) as opposed to specific activities, such as violin performance. Moreover, even the more relevant or field related studies that could provide some correlation to this particular population are inadequate in providing definitive diagnosis, treatment plans, or equally important potential preventative measures. Where attempts have been made to link “abnormal” motion to injury in musicians, these motions have not always been described in clinically relevant terms, have not been assessed in three dimensions, and their relationship to pathology has not been made apparent.

Modern ergonomics further subdivides exposure into external exposure (outside factors that affect the worker but are independent from the worker), and internal exposure (forces and torques that exist in an individual worker) (Anton, 2002 b). Low force, repetitive work that is performed over several hours is common and has been evaluated using various exposure methodologies, including observation, videotaping, and measurement of actual physiological parameters. The understanding of exposure has therefore evolved in the last three decades to include evaluation of internal factors such as muscular load, joint displacement, heart rate, and perceived exertion. None of the common methods of evaluation have been successfully employed to determine the exposure of musicians to musculoskeletal disorders that are so commonly reported.

Few ergonomic interventions are available to the health care practitioner for the musician population. The design of orchestral instruments is not likely to change, and musical repertoire, which determines the performance exposure, will not change. Education of the musician regarding practice and performance strategies, basic anatomy and physiology, optimal playing posture, and the utilization of various prosthetic devices, such as chin rests and shoulder rests, may help reduce the incidence or impact of musculoskeletal disorders that are often reported by this population. Although the factors of position, performance style, etc. have been identified as possible causes of these types of musculoskeletal injuries, these assumptions cannot be used as the basis for definitive diagnosis and treatment unless more reliable information regarding muscle utilization and joint motion is available. Education may then be targeted to address the needs of the individual musician rather than the generic group.

Musicians are apparently reluctant to report injuries because of repercussions that may ensue, such as omission from orchestra performances, adverse effects on their grades (in the case of students), potential loss of income, stigma of disability, and perhaps even the need for surgery or other invasive procedures or investigations (Middelstadt and Fishbein, 1989, Lederman, 1987). Therefore, it is possible that the injury prevalence reported in the literature is underestimated. Lederman (1987) reported that the number of subjects seen with thoracic outlet syndrome (TOS) varies widely and he alludes to the possibility that the reported numbers may be inaccurate.

Studies reporting the incidence of injury in musicians have relied on anecdotal clinical observations or on a subjective questionnaire format of evaluation (Norris, 1993; Quarrier, 1993; Brandfonbrener, 1990; Mandel, 1990; Lockwood, 1989; Fry, 1989; Hoppmann and Patrone, 1989; Meador, 1989; Gorman and Warfield, 1987; Elbaum, 1986; Fry, 1986 (a); Fry, 1986 (b)). These reports are inconclusive and do not present a satisfactory explanation as to the cause of the injury or the treatment applied to alleviate the symptoms. Interestingly, these observations do not necessarily apply to all musicians who play the same instrument. Furthermore, these studies do not identify a specific diagnosis, but rather list the area(s) of discomfort experienced by each musician. In the reporting process it may be assumed that the investigators required participants to cite an area, or areas, of the body where they were experiencing discomfort, rather than fully examining the participant in an effort to make a definitive diagnosis.

Anecdotal and case study designs have been generalized to broad samples of the musician population and reliance on the musician’s perception of pain does not allow for the possibility that the pain may be referred. While some of these studies provide recommendations as to how injured musicians should be treated or how injuries should be prevented, these recommendations are based on anecdotal rather than reliably determined results. Both the diagnoses and the treatment recommendations are therefore of limited value to clinicians and researchers.

Injury Implication

Research indicates that musicians suffer a myriad of disorders related to their profession (Middelstadt and Fishbein, 1989; Fishbein et al, 1988; Hiner et al, 1987). Some of these include musculoskeletal disorders (MSD), but others include performance anxiety and disorders related to aging.

Musculoskeletal Disorders (MSD)

Questionnaire studies indicate that MSDs, particularly those of the upper extremities, are common amongst orchestral violin musicians (Middelstadt and Fishbein, 1989; Fishbein et al, 1988; Hiner et al, 1987). In the study performed by Hiner (1987) six of fifteen violinists, polled from an elite group of musicians attending an international competition who had reported a performance limiting injury, cited a history of shoulder disorder. Five of the six affected violinists cited bow control (right shoulder) as being a major contributor to their shoulder problems. Middelstadt and Fishbein (1989) reported that 20% (424) of respondents in a nationwide poll of professional musicians (of whom 2122 musicians returned questionnaires) reported right shoulder problems (13%, or 275 of these being regarded as severe by the musicians). The investigators indicated that musicians attributed these injuries to performance and practice, and most indicated that the injuries adversely affected their performance. Some studies also indicated that factors such as the instrument design (Blum and Ahlers, 1994), awkward performance posture (Lockwood, 1989; Castleman 2002), high levels of musculotendinous tension (Castleman, 2002; Hartsell and Tata, 1991), and asymmetric loading of the cervical spine (Bejjani1989) also contribute to these injuries.

Castleman (2002) listed five causes of injury in violists, namely improper instrument fit, faulty practice habits, poor body support of the instrument, holding the instrument by squeezing rather than balancing, and squeezing with the thumbs. However, few objective studies have been able to explain any consistent association between MSD's and these factors. Despite this, the injury incidence is a concern to the musician population, especially considering that violinists and violists comprise the largest proportion of musicians in the orchestra. Middelstadt and Fishbein (1988) reported that of the 2122 musicians that returned questionnaires in their national poll of symphony orchestras in the United States, 65% of these musicians were string instrumentalists. These findings were consistent across orchestras of all sizes. Of these musicians, 695 (32% of the entire sample) were violin players.

Subacromial Impingement Syndrome

Subacromial Impingement Syndrome (SIS) is the most common cause of shoulder pain (Michener et al, 2003). SIS, which is reportedly common in the right (bowing) shoulder of violinists (McFarland and Curl, 1998), subsumes such disorders as subacromial bursitis, supraspinatus tendonitis, and rotator cuff tendinitis involving tendons other than supraspinatus. SIS refers to the suprahumeral compression of structures between the anterior and inferior aspect of the acromion process, which includes the rotator cuff tendons, most specifically the supraspinatus tendon, and or muscle, the long head of biceps, and the subacromial bursa (Neviaser and Neviaser, 1989). The relative motion of the glenohumeral and scapulothoracic joints is complex under dynamic conditions (Karduna et al, 2001).

Bowing with the right upper extremity when playing the violin comprises rhythmic horizontal-flexion and -extension of the right upper extremity as the bow is drawn back and forth across the strings of the instrument. This also involves varying degrees of scapula plane elevation of the right upper arm, the degree of which depends on which string is being played on and whether the musician is playing on the “up-bow”, which should require more glenohumeral horizontal flexion and scapula plane elevation, or the “down-bow”, which reportedly involves more horizontal extension and less scapula plane elevation (Tulchinsky and Riolo, 1994). This in turn theoretically requires that the glenohumeral joint be placed in varying degrees of internal rotation in the elevated position (more internal rotation for the bass strings and less internal rotation for the treble strings), a maneuver that mimics the Hawkins-Kennedy impingement test (Hawkins and Kennedy, 1980; Calis et al, 2000), which, like the musician’s movement, is believed to cause a decrease in the subacromial space as the greater tuberosity approaches the antero-inferior acromion.

Shoulder Joint Biomechanics

Studies using three-dimensional kinematic analysis have indicated that scapulothoracic dyskinesia, or malalignment of the scapula on the thorax, may be associated with a higher incidence of SIS (Lukasiewicz et al 1999; Ludewig and Cook, 2000; Karduna et al, 2001). Specifically, those research participants with shoulder impingement syndrome demonstrated several aspects indicating dyskinesia, including decreased posterior scapula tilting (Ludewig and Cook, and Lukasiewicz et al), increased elevation of the scapula during arm elevation (Lukasiewicz et al), decreased scapula upward rotation at around 60^o scapula plane elevation, increased anterior tilting at around 120^o elevation, and increased scapula medial rotation under loaded conditions (hand held loads of 2.3 and 4.5 kg) throughout scapula plane elevation (Ludewig and Cook, 2000). Ludewig and Cook (2000) used surface mounted electromagnetic sensors to record motion of the scapulothoracic “joint” using ordered Cardan and Euler angle rotation sequences about mathematically embedded local coordinate systems (LCS) within the bony segments (thorax, scapula and humerus), in accordance with the International Biomechanics Society recommendations for three-dimensional kinematic analysis (as proposed by van der Helm 2001). Lukasiewicz et al (1999) used a projection angle method of motion analysis whereby the subject’s scapula position was repeatedly tracked by digitizing bony landmarks at various scapulothoracic positions.

Ludewig and Cook (2000) also demonstrated that participants with SIS demonstrated decreased serratus anterior ($p<0.05$), and increased upper and lower trapezius ($p=0.05$) electromyographic activity than those without impingement syndrome. This suggested that those with SIS over-recruited the upper and lower trapezii and failed to adequately recruit the serratus anterior, thus allowing the scapula to rotate downwards, tilt forward (or fail to tilt backwards sufficiently) and rotate medially during motion, compared to those without SIS.

Open magnetic resonance (MR) analysis of the shoulder has been used to show that activation of the rotator cuff muscles (comprising supraspinatus, infraspinatus and teres minor) at around 90 degrees of glenohumeral abduction, resulted in narrowing of the subacromial space in subjects with full thickness rotator cuff tears and/or subacromial impingement (Graichen et al, 1999). This finding was not observed to the same extent in uninjured subjects. Such rotator cuff activation is likely to occur in the right upper extremities of violin musicians during the “up-bow” phase of bowing on the G-string, and to a slightly lesser extent, D-string, which, when the musician is observed, appears to result in glenohumeral joint scapula plane elevation, horizontal flexion and internal rotation, and the scapulothoracic joint in internal rotation and possibly upward rotation. If this is in fact the case, then these observed motions would concur biomechanically with motions that have been found to be associated with SIS (Ludewig and Cook, 2000).

To date, attempts to investigate biomechanical factors associated with bowing in string musicians have met with some limitations. Tulchinsky and Riolo (1994) used a two-dimensional (2-D) camera technique utilizing one camera and reflective skin markers to track the motion of the bow arm (right arm) in 9 uninjured female professional violinists. The technique was limited by the slow speed of the camera (shutter speed 1/250 s) and the fact that there was only one camera, resulting in greater projection angle-type error in the motion tracking. Furthermore, individual bowing techniques were not accounted for in the study. The researchers assessed motion in the sagittal plane only, and since motion in the bow arm is multi-planar at both the scapulothoracic and glenohumeral joints, this technique is not optimal for tracking the complex motion of the bow arm during violin performance.

A more recent study failed to adequately control error associated with the projection angle method of analysis (Turner-Stokes and Reid, 1999). The study was reportedly a, “three-dimensional study of the biomechanics of the right shoulder during bowing”, yet the use of two video cameras necessitated two “takes” to capture the motion of the bowing action, and failure to create three-dimensional local coordinate systems (LCS) in each bony segment of the shoulder joint complex rendered this a two dimensional, rather than the reported three-dimensional, investigation. Despite the fact that the authors reported having devised a reproducible representation of the motion of the shoulder complex, they only reported the range of motion of each joint in one direction, and it is not clear what reference system these motions were compared to, or what they comprised (elevation, internal/external rotation or abduction, or a combination of these three). Therefore, the utility of this measure has limited value in clinical practice, and would be difficult to replicate. The authors attempted to determine possible causes of shoulder impingement in this population. It is not evident that this was satisfactorily achieved. Furthermore, the experimental task for the study was not representative of the repertoire that is commonly played. Okner listed the playing of repertoire for research studies that is not commonly played by musicians as a possible limitation in her study (Okner, 1997).

Shan and Visentin (2003) attempted to assess the three-dimensional arm kinematics during violin performance of standardized scales. The investigators arranged nine synchronized cameras around the musician. Reflective markers were affixed to various bony segments of the shoulder complex as well as on the instrument and bow. The investigators reported having reliably measured complex shoulder motions using single reflective markers on each shoulder segment. Because they did not mathematically embed a local coordinate system (LCS) into each shoulder segment, they were effectively prevented from extracting an adequate three dimensional measurement of inter-segmental scapulothoracic or glenohumeral displacement along, or rotation about, their three respective orthogonal axes. As a consequence, this lack of data limited their identification of the mechanics associated with SIS, since it has been shown that SIS is associated with scapula downward rotation and reduced posterior tilting during glenohumeral elevation in the scapula plane (Ludewig and Cook, 2000).

Shan et al (2004) used the same biomechanics technique in a more recent study to simultaneously assess kinematic, kinetic, electromyographic and sound data in violin musicians. They made predictions about muscle length based on the videographic evaluation of kinematic data which is open to projection angle error, as is the evaluation of joint kinematics without embedding the local coordinate systems within the segments under investigation. Lastly, their electromyographic signal was not pre-amplified before it was transmitted telemetrically to a nearby receiver unit; interference with ambient noise in the recording area may have adulterated the results. It is doubtful that this can be regarded as a truly 3-dimensional study since they did not embed local coordinate systems in shoulder segments. Omission of this factor represents a significant limitation from a clinical perspective.

Shan et al (2004) also reported the use of inverse dynamic analysis and the mathematical calculation of joint moments during violin performance to predict forces (kinetics) in the shoulders, yet no force readings were made: these moments were modeled after kinematic data and inertial characteristics of the body based on anthropometric normative data. Additionally, the researchers (Shan and Visentin, 2003) assessed peak displacement of joint motions in the performance of the scale, rather than observing the relative period of time spent at various ranges of motion, as may have been possible with an exposure variation analysis (EVA) (Mathiassen and Winkel, 1991). Performers in this study may have briefly moved the joint in question to a particular extreme point in the range, yet may have spent a majority of the performance time at more comfortable or acceptable ranges than the extreme. This may tend to misrepresent the exposure of the joint to awkward posture.

Planar videographic methods of kinematic analysis are prone to projection angle error (Shan and Visentin, 2003). Euler's angles (encompassing Cardan angles) offer a more efficient and accurate method of representing kinematics of human motion with less redundancy (Zatsiorsky, 1998). The use of multiple video cameras, as used by Shan and Visentin, helps to reduce this error, but failure to create local coordinate systems using techniques described by Craig (1989), Zatsiorsky (1998), van der Helm (2001) and Ludewig and Cook (2000) suggests that the kinematic methods used by Shan and Visentin were not adequate for accurate motion analysis in a precise task such as violin bowing. Musical repertoire is regarded as being an important consideration in establishing the exposure of the musician to performance hazards: Shan and Visentin (2003) and Shan et al (2004) used rudimentary scales as performance repertoire rather than using more representative musical scores to assess the musicians. This too has been cited as a potential limitation in the assessment of the musician to performance related hazards (Okner, 1997).

It appears that the optimal method of assessing the effect of inter-segmental shoulder motions on SIS in violin musicians is to track these motions in three dimensions using standardized Euler and Cardan ordered rotation sequences about embedded localized coordinate systems (LCS). No previous studies have identified the relative motion of these joints in an occupational task with suitable accuracy. Since most occupations are poorly simulated in the laboratory environment, studying musicians in laboratory simulation may lack validity. This is also made particularly difficult in the confined “electromagnetic envelope” (a hemisphere of approximately 76-cm about the electromagnetic transmitter used in the three dimensional assessment) within which the “worker” needs to operate for this method of motion analysis to be employed. The task of playing a stringed musical instrument lends itself to this analysis since the musician is able to play in a seated or standing position and remain within the electromagnetic envelope of the electromagnetic transmitter for the duration of the occupational task. Furthermore, this is achieved in the absence of ferrous metals, which may distort the electromagnetic signal, and therefore introduce systematic error in the data collection.

Upper Trapezius and Serratus Anterior Electromyography

Investigations of shoulder muscle use in violinists have provided conflicting results. All of the studies to date have utilized a temporal method of electromyographic (EMG) data analysis and most have been poorly standardized with respect to variability in the individual musician’s muscle activation (Berque and Gray, 2002; Philipson et al, 1990; Levy et al, 1992). Berque and Gray (2002) investigated the upper trapezius muscle activation in a group of professional violinists (n=5, 2 male, 3 female) and violists (n=5, 2 male, 3 female) using surface EMG. The researchers used normalization techniques similar to those used by previous researchers (Mathiassen and Winkel, 1995; Bao et al, 1997, Mathiassen and Winkel, 1995) to standardize the comparison of one musician to another. They did not, however, utilize onsite pre-amplification close to the EMG electrodes, and they used a reference electrode site close to active muscles from which they were recording. The resulting possible muscle activation interference through the reference electrode would thereby possibly introduce inadvertent error. Moreover, the investigators based the exposure of the upper trapezius on the mean EMG for the performance of test repertoire: EMG amplitude may vary depending on the dynamics with which the musician chooses to play, as well as the intensity of the music. The level of EMG recorded would thereby be impacted by style, rather than minimal demand. No information regarding the variability of the EMG is gained from this method of analysis, and this variability may partially explain why some musicians are able to play with relatively high levels of average EMG and not display signs of injury, as was shown by Berque and Gray (2002). However, other studies indicate that musicians who use relatively high levels of average EMG display signs of injury (Philipson et al, 1990; Levy et al, 1992). This would seem to suggest that higher levels of average upper trapezius EMG is not closely associated with injury, but failure to adequately survey all factors associated with the variability of muscle activation in work tasks may adversely affect the utility of this method of analysis.

Exposure Variation Analysis

The limitations of temporal data reduction with electromyography (EMG) and other outcome variables, such as range of motion, have been well documented (Mathiassen and Winkel, 1991; Hägg et al, 1997; Bao et al, 1997; Jansen et al, 2001). Researchers typically evaluate differences between two or more groups based on mean, median, maximum, minimum or mathematical manipulations of the data (fast Fourier transform) to make inferences about the groups' makeup. Whilst this information is interesting, it describes the data in one dimension only, and may not necessarily identify a factor that has clinical relevance. For example, knowing what the mean or maximum value in an EMG data signal may not be representative of the task being evaluated, as the maximum may have been achieved for a very brief time. The mean would then be more useful, but also may not be representative of the exposure during the task.

Several researchers have used a data reduction technique known as exposure variation analysis (EVA) to explain the variability in factors such as EMG and joint range of motion in terms of amplitude and repetition in various occupational settings (Anton, 2002b; Mathiassen and Winkel, 1991; Mathiassen and Winkel, 1996; Bao et al, 1997; Hägg et al, 1997; Hägg and Åström, 1997). EVA is regarded by these researchers as being an appropriate method of exposure analysis because of the simultaneous assessment of amplitude variability and duration of time spent at different amplitude levels. EVA has been successfully used to establish the efficacy of ergonomic interventions in various assembly jobs (Mathiassen, SE and Winkel, J, 1996; Bao et al, 1997), nursing service, housekeeping and office work (Jansen et al, 2001), construction jobs (Anton, 2002 b), and office occupations (Hägg and Åström, 1997, Jensen et al, 1999).

Mathiassen and Winkel (1996) used EVA as an additional data reduction method in a laboratory simulation of light assembly work in 8 asymptomatic women with no assembly experience: the EVA method successfully predicted a change in mechanical exposure when work pace was changed. Bao et al (1997) used the EVA method to contrast assembly line design in Sweden and China. Swedish workers used upper trapezius and infraspinatus muscles with more repetition, whereas Chinese workers used a larger proportion of low level muscle activation in these muscles for the same tasks. The mean amplitude of upper trapezius activation was the same, indicating that regular observation of the EMG signal may not have revealed the subtle changes in repetition that the EVA method was able to detect. In a more recent study using innovative statistical methods, Jansen et al (2001) used EVA to analyze spinal inclinometric data in the sagittal plane in nurses, housekeepers and office workers. Again, analysis of the amplitude and frequency with which amplitude changed presented the researchers an opportunity to assess exposure in multidimensional terms which has previously been ignored.

Anton (2002 b) used EVA data reduction to assess upper extremity muscle exposure in mechanics and heavy equipment operators. Using a sophisticated “cluster” categorization of varying levels of intensity and duration (frequency), he was able to demonstrate differences in the two construction trades relative to differing work demands.

Hägg and Åström (1997) and Jensen et al (1999) used EVA methods to differentiate between upper trapezius muscle activation level and contraction duration (repetition) in computer aided design (CAD) workers to the same factors in industrial production workers. As a secondary point of comparison, they distinguished between the mouse-side (the hand that uses the “mouse” to control the cursor on the computer screen) and non-mouse-side of CAD workers. The analysis indicated more repetitive muscle activation in the production workers than CAD workers, and CAD workers adopted sustained duration low amplitude muscle activation. Side-to-side comparison in CAD workers indicated sustained muscle activation on the mouse side, and gap analysis, which involves counting the number of periods of at least 0.2 seconds of EMG activity below 0.5% of maximum voluntary contraction (MVC) (Veierstedt et al, 1993). Veierstedt et al (1993) indicated an inverse correlation between the number of gaps and the incidence in shoulder pathology.

In a recent pilot study on violin and viola musicians, Reynolds and Ludewig (2002) used exposure variation analysis (EVA) data reduction methods to investigate the exposure of violinists and violists to upper trapezius and serratus anterior muscle exposure, and scapulothoracic and glenohumeral joint exposure to standardized repertoire performance. The results of this analysis indicated that the potential to develop a model for the utilization of EVA in assessing exposure in this population exists.

Studies to determine the exposure of violinists to awkward posture and kinematics, and high EMG exposure have been poorly controlled and have made erroneous assumptions with respect to causal relationships to injury. Furthermore, the use of peak measurement of joint excursion is misleading in terms of assessing the exposure of the musician to awkward postures during performance. Temporal analysis of average EMG exposure in such cases is also misleading. Musicians interpret and express musical dynamics differently and may therefore utilize varying amounts of muscular recruitment in the performance of the same repertoire. Vibrato is used to give music a vocal quality and will likely result in increased recruitment and rate coding when used, thus increasing the EMG amplitude and/or frequency in the involved muscles.

Clearly, normalization and standardization methods are required to allow the researcher to make equitable comparison that is more representative of true exposure. As with kinematic analysis, time spent at varying amplitude levels has been shown to be a more representative measure of exposure since it simultaneously expresses the task in terms of amplitude and duration, both important measures of exposure.

Exposure Variation Analysis methods have not been used successfully thus far in the determination of exposure to abnormal muscle and kinematic variables in a population of musicians. The evaluation of the kinematic and electromyographic variables in the right shoulder complex was regarded as being important in gaining an understanding of the pathomechanics of SIS in the right shoulders of violinists. EVA is therefore the data reduction technique utilized in this study to assess the exposure of violinists to right shoulder SIS.

Hypotheses

Introduction

Participants in this study represented two groups, injured (those presenting with symptoms of subacromial impingement syndrome (see *Inclusion Criteria* in Chapter 3) and non-injured. Each participant performed the slow and fast repertoire 4 times each in a random sequence. The slow repertoire was played at 60 beats per minute and lasted 30 seconds. The fast repertoire, which comprised the same notes as the slow repertoire played 8 times through at 160 beats per minute. Each trial also lasted 30 seconds.

Repeatability of the EVA technique

Hypothesis 1

EMG EVA (EEVA) for upper trapezius and serratus anterior muscles and kinematic EVA (KEVA) for various scapulothoracic and glenohumeral kinematic variables will demonstrate good repeatability of the EVA technique.

Repertoire Speed Differences

Hypothesis 2

Significant between-speed within-subject differences in EEVA and KEVA will be observed with respect to EMG exposure variation analysis (EEVA) in the right upper trapezius and right serratus anterior muscles, and kinematic exposure variation analysis (KEVA) in the scapulothoracic and glenohumeral joints. Acceptance of this hypothesis will indicate that the EVA technique may be used to determine differences in repertoire speed when the same repertoire is played at two differing speeds.

Muscle Exposure

Hypothesis 3

Classification of injured and non-injured violinists will significantly predict differences in muscle exposure in terms of sustained levels of right upper trapezius activation (high and/or static amplitude and long duration, or static activation, in the injured group, versus low and/or dynamic amplitude and shorter duration, or dynamic activation in the non-injured group) during standardized musical performance at both slow and fast speeds.

Hypothesis 4

Classification of injured and non-injured violinists will significantly predict differences in muscle exposure in terms of sustained levels of right serratus anterior activation (low and/or dynamic amplitude and shorter duration, or dynamic activation in the injured group versus high and/or static amplitude and long duration, or static activation in the non-injured group) during standardized musical performance at both slow and fast speeds.

Kinematic Exposure

Hypothesis 5

Classification of injured and non-injured violinists will significantly predict differences in kinematic exposure in terms of self-selected range of operation and sustained levels of scapulo-thoracic “joint” exposure: it is anticipated that the injured group will demonstrate a tendency towards long and/or static durations of increased anterior tilting (tipping) of the scapula in relation to the trunk, and/or increased downward scapula rotation (or less upward rotation), and that the uninjured group will demonstrate a tendency towards shorter and/or dynamic periods of scapular tilting, with less anterior tilting of the scapula in relation to the trunk, and/or increased upward scapula rotation during standardized musical performance at both slow and fast speeds.

Hypothesis 6

Classification of injured and non-injured violinists will significantly predict differences in kinematic exposure in terms of self-selected range of operation and sustained levels of glenohumeral joint exposure: the injured group will display a tendency towards long and/or static durations of increased elevation and internal rotation of the humerus relative to the scapula, and the uninjured group will display a tendency towards shorter and/or dynamic periods of glenohumeral elevation and internal rotation of the humerus (less rotation) relative to the scapula during standardized musical performance at both slow and fast speeds.

Rationale

This and further study will help to identify factors closely related to the presence of right-sided shoulder impingement disorders in string musicians. It is expected that these factors may comprise scapulothoracic and/or glenohumeral dyskinesia (anterior tipping of the scapula relative to the trunk, downward rotation of the scapula relative to the trunk, internal rotation of the humerus relative to the scapula, abduction of the humerus relative to the scapula, or a combination of these awkward postures and motions) and abnormal upper trapezius and serratus anterior activation (increased and static activation of the upper trapezius and less activation of the serratus anterior compared to asymptomatic musicians). These in turn may support the presently accepted belief that these injuries are related to awkward posture, repetition, static posture and forceful exertion. This is important because the true causes or effects of musculoskeletal disorders in musicians have been inadequately determined and the number of musicians playing with pain, taking medication to relieve stress and/or pain, or prematurely terminating highly promising careers is high. This information may be used to plan further research that may guide clinicians in advising musicians and music instructors on injury prevention.

Definition of Terms

A description of terms used in this document follows:

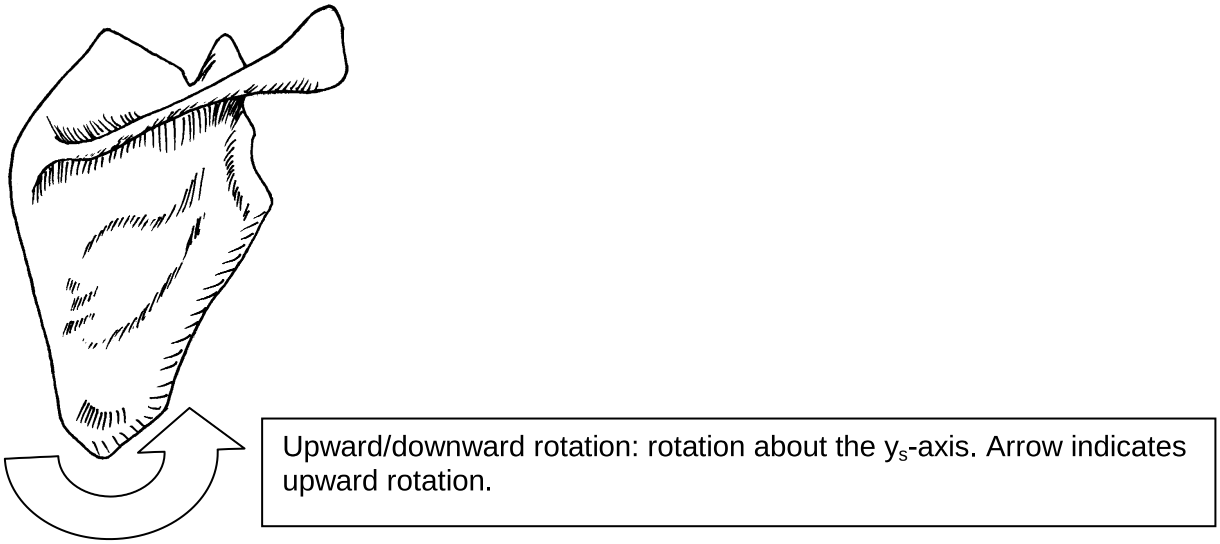
1. Subacromial Impingement Syndrome (SIS): compression of soft tissue structures between the humeral head and the undersurface of the acromion process and/or the coracoacromial ligament.
2. Subacromial space: the area between the inferior border of the acromion process and the superior aspect of the humeral head, incorporating the soft tissue.
3. Coracoacromial arch: the inferior border of the acromion, the coracoacromial ligament and the posterior aspect of the coracoid.
4. Scapula upward/downward rotation: rotation of the right scapula about the locally embedded ys axis. Positive rotation denotes downward rotation relative to the trunk (thorax) (Figure 1.1).
5. Scapula internal/external rotation: rotation of the right scapula about the locally embedded zs axis. Positive rotation denotes internal rotation relative to the trunk (thorax) (Figure 1.2).
6. Scapula anterior/posterior tilting: rotation of the right scapula about the locally embedded xs axis. Positive rotation denotes posterior tilting relative to the trunk (thorax) (Figure 1.3).

7. Arm elevation: elevation of the humerus relative to the trunk (thorax) about the locally embedded yh axis (Figure 1.4).
8. Arm plane elevation: rotation of the humerus relative to the trunk (thorax) about the locally embedded zh axis (Figure 1.4).
9. Arm internal/external rotation: rotation of the humerus relative to the trunk (thorax) about the locally embedded zh axis (Figure 1.4).
10. Glenohumeral flexion/extension: rotation of the right humerus relative to the scapula about the locally embedded xh axis. Positive rotation denotes flexion of the humerus relative to the scapula (Figure 1.4).
11. Glenohumeral abduction/adduction: rotation of the right humerus relative to the scapula about the locally embedded yh axis. Positive rotation denotes extension (Figure 1.4).
12. Glenohumeral internal/external rotation: rotation of the right humerus relative to the scapula about the locally embedded zh axis. Positive rotation denotes internal rotation (Figure 1.4).
13. Glenohumeral internal/external rotation: axial rotation of the humerus relative to the scapula about the locally embedded zh axis. Positive rotation denotes internal rotation (Figure 1.4).

Scapula Orientation

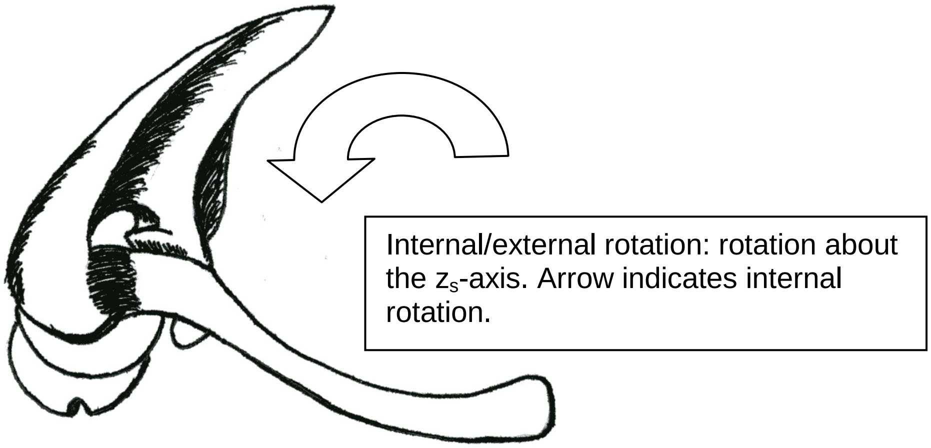
The following figures describe scapula rotation orientations that are described above and that are used in this document.

Figure 1.1. Scapula upward/downward rotation



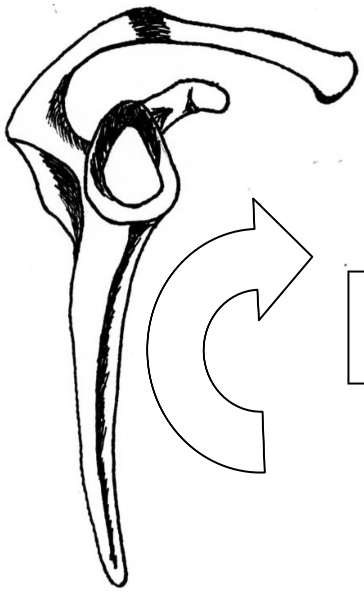
Upward/downward rotation: rotation about the y_s-axis. Arrow indicates upward rotation.

Figure 1.2. Scapula internal/external rotation



Internal/external rotation: rotation about the z_s-axis. Arrow indicates internal rotation.

Figure 1.3. Scapula anterior/posterior tilting

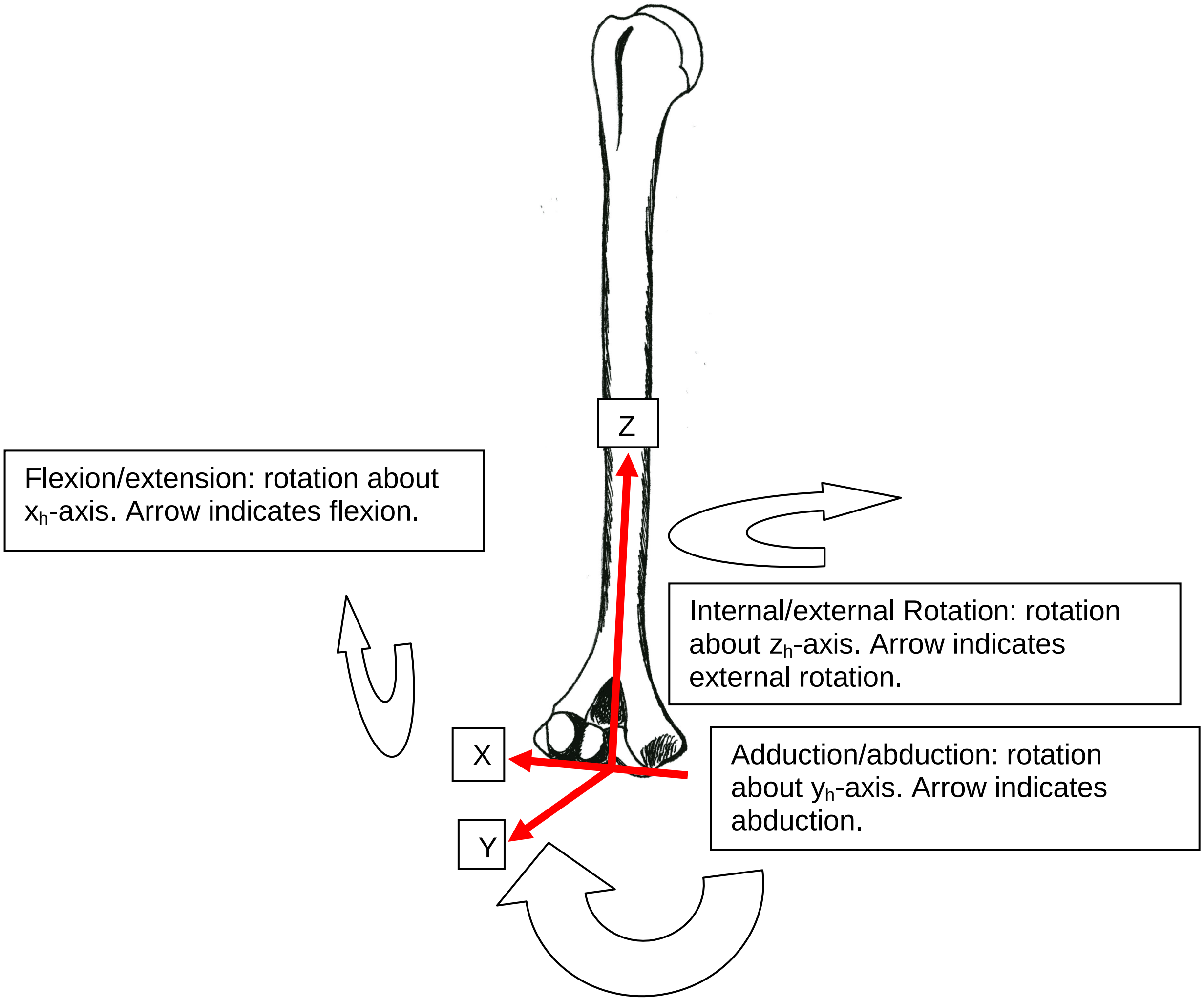


Anterior/posterior titling: rotation about the x_s-axis. Arrow indicates anterior tilting.

Humerus Orientation

The following figures describe humeral rotation orientations that are described above and that are used in this document.

Figure 1.4. Right humerus viewed from the front showing orientation of axes



Flexion/extension: rotation about x_h-axis. Arrow indicates flexion.

Internal/external Rotation: rotation about z_h-axis. Arrow indicates external rotation.

Adduction/abduction: rotation about y_h-axis. Arrow indicates abduction.

Abbreviations

Abbreviations used in this document are described below:

Term	Explanation
3-D	Three Dimensional
ACJ	Acromioclavicular joint
AMA	American Medical Association
ANOVA	Analysis of Variance
APDF	Amplitude Probability Distribution Function
BMI	Body Mass Index
C7	Spine of the seventh cervical vertebra
Ca2+	Calcium
CAD	Computer Aided Design
CEVA	Cluster Exposure Variation Analysis
CFA	Contract Frequency Analysis
DDF	Denominator Degrees of Freedom
EEVA	Electromyographic Exposure Variation Analysis
EMG	Electromyography
EVA	Exposure Variation Analysis
GCS	Global Coordinate System
GHJ	Glenohumeral joint
HFF	High Frequency Fatigue
IRB	University of Minnesota Institutional Review Board
JASA	Joint Analysis of EMG Spectrum and Amplitude

KEVA	Kinematic Exposure Variation Analysis
LCS	Local Coordinate System
LFF	Low Frequency Fatigue
MANOVA	Multiple Analysis of Variance
MMT	Manual Muscle Test
MRI	Magnetic Resonance Imaging
MSD	Musculoskeletal Disorder
MTM	Methods Time Measurement
MVC	Maximum Voluntary Contraction
MVE	Maximum Voluntary Electrical Activity
NDF	Numerator Degrees of Freedom
NDI	Neck Disability Index
PPT	Pressure Pain Threshold
PLA`	Postero-lateral acromion
PRMD	Performance Related Medical Disorders
RMS	Root Mean Square
RSA	Right Serratus Anterior
RSA	Right Serratus Anterior
RSS	Root of the spine of the scapula
RUT	Right Upper Trapezius
RVE	Relative Voluntary Electrical Activity
SAS	Statistical Analysis Software
SIS	Subacromial Impingement Syndrome
SN	Sternal Notch

SRQ	Shoulder Rating Questionnaire
T8	Spine of the eighth thoracic vertebra
TOS	Thoracic Outlet Syndrome
VAS	Visual Analog Scale
xh	Embedded x-axis of the humeral local coordinate system (LCS)
xs	Embedded x-axis of the scapula local coordinate system (LCS)
xt	Embedded x-axis of the trunk local coordinate system (LCS)
yh	Embedded y-axis of the humeral local coordinate system (LCS)
ys	Embedded y-axis of the scapula local coordinate system (LCS)
yt	Embedded y-axis of the trunk local coordinate system (LCS)
zh	Embedded z-axis of the humeral local coordinate system (LCS)
zs	Embedded z-axis of the scapula local coordinate system (LCS)
zt	Embedded z-axis of the trunk local coordinate system (LCS)

CHAPTER 2

LITERATURE REVIEW

Musculoskeletal disorders (MSD) are common amongst orchestral musicians (Fry, 1987, 1989; Hiner, 1987; Fishbein et al, 1988; Middelstadt and Fishbein, 1989; Hartsell and Tata, 1991; Cayea and Manchester, 1998; Ziporyn, 1984, Dawson, 1988). Fry (1987) described overuse of the muscles, ligaments, and joints in the upper extremities of music students and suggested that genetic factors, technique, and time and intensity of practice were the main contributors to this problem.

In a questionnaire study returned by 29 of the 55 (52.7%) polled “premier violinists” who attended the 2nd Quadrennial International Violin Competition (Hiner, 1987), 15 (51.7%) responded that they had experienced a performance-limiting injury. Right upper extremity complaints, mostly pain, were common and the most common sites of injury reported were the wrists and shoulders. Surprisingly, most of these right-sided complaints were not attributed to bowing and bow control during performance. However, of the 5 respondents who reported shoulder-specific problems, 2 were right sided only, 1 was left sided only, and 2 were affected bilaterally.

Middelstadt and Fishbein (1989) performed what appears to be the largest questionnaire study of orchestral musicians. They polled over 4,000 professional musicians employed by 48 symphony orchestras in the United States. Responses from 2,212 (55%) musicians were studied. Thirty-one percent of the respondents (695) were violinists, and, of these, 16% reported severe right sided shoulder problems, more than any other location in the body. Of the total sample, 205 (9.3%) were violists and, of these, 16% reported severe right shoulder problems (Middelstadt and Fishbein, 1989). Overall injury incidence was reported to be more prevalent in female string instrumentalists than in their male colleagues. Diagnoses were not sought or confirmed in this study, thereby making inferences about these problems impossible.

Cayea and Manchester (1998), Manchester (1988), Manchester and Flieder (1991) and Hartsell and Tata (1991) investigated injury incidence gleaned from medical records of music students retained at the student health clinics of their respective universities. Cayea and Manchester (1998) found that violinists (106/1,028 or 10.3%) had of the highest injury rates in the student population between 1982 and 1996. Only harpists (15/88 or 17%), guitarists (6/44 or 13.6%), pianists (138/1,052 or 13.1%), and double bassists (22/212 or 10.4%) had higher injury rates. Violists accounted for 9.7% (45/462) of the injuries seen. Females (9.3 % or 50/536) had a higher incidence rate than males (7.7 % or 18/234), though this was not a significant difference. The authors suggest that this had to do with the relative size of the instrument in relation to the musician. These rates are not as high as those seen in a study by Fry (1986 a, b or c), where injury incidence rates were 75% for both violinists and violists. The results of that study are more in agreement with a later study on Australian music schools by Fry (1987) where the injury incidence was 8% for string instruments.

Manchester and Flieder (1991), in an epidemiological study on university level music students between 1985/6 and 1988/9 found that left-sided injuries were more common than right-sided injuries in student violinists and violists, and that the incidence of injury amongst string musicians was second only to keyboardists. Over the course of the period studied in students, of the 114 students seen, 41 men and 73 women were seen for 44 and 78 episodes of performance related discomfort respectively. Violin and viola injuries were more common than all other instrument groups (66 of 175 or 37.7%) and right shoulder injuries (3% or 5/175 of total injuries) were less common than piano/organ (3.4% or 6/175), but more common than cello/bass and woodwinds (1% or 2/175).

Similar results were found by Dawson (1988) in a research study performed at a major university arts medicine facility in the United States. A broad cross-section of musicians (totaling 148), from professional performers and teachers to amateurs, were seen. Of these, 32 (21.6%) were string musicians, accounting for the second highest incidence (keyboardists accounted for 56% (83/148) of injuries. More violinists were injured than any other string instrument group. Overuse injuries were found to be common (27.7% or 41/148) second only to trauma (46.6% or 69 of 148 cases). Other studies have paid less attention to the inclusion of these other diagnoses.

In a retrospective questionnaire study (Hartsell and Tata, 1991), 122 of 300 questionnaires were returned by undergraduate male and female music student participants at the University of Western Ontario, Canada. Violin students encountered the second highest incidence of music performance related problems, with a per capita injury rate of 42.1%, second only to piano students (57.4%). A notable difference with this study was that students were required to study more than one instrument if enrolled in this university's music program. This makes determination of the instrument most related to possible cause of the injury challenging. Violinists experienced predominantly shoulder injuries with 25% (6/24) reporting pain in this region. The side of shoulder injury was not mentioned in the study which makes it difficult to assess which action (fingering or bowing) was responsible for the injury. This is a disappointing omission if one is to gain useful information about injury prevention from the study. Most of the violin injuries were attributed to muscular problems alone, as opposed to neurological problems or a combination of muscular, neurological, or other causes. According to information derived from the questionnaire, perceived causes of injury amongst violinists were posture, technique and playing habits.

These studies suggest that complaints in the upper extremities of violinists and violists are more prevalent than in other anatomical regions. This is particularly the case with hand problems in female violinists and violists (Manchester and Flieder, 1991). In general, musicians seem to attribute these injuries to performance and practice habits, abnormal posture, and technique (Hartsell and Tata, 1991), and most indicate that the injuries affect their performance adversely (Middelstadt and Fishbein, 1989). The injury rate amongst university string musicians is particularly high, especially those of the violin musicians (Hartsell and Tata, 1991; Manchester, 1988; Cayea and Manchester, 1998). However, few objective studies have been able to provide any reliable information about possible causes of, or reliably successful treatments for, these injuries. This is possibly because these studies are not controlled and rely on anecdotal information derived from medical records. They also fail to mention or control for other extramural and daily activities that the musicians may indulge in, such as computer use, part-time occupations, recreational activities, concomitant disease, or past medical history. In addition, they do not account for the different methods/styles that violinists and violists utilize to grasp their instrument between the left shoulder and chin.

Studies using a questionnaire design have indicated that higher injury rates among musicians may be caused by numerous and varied factors including anthropometric mismatch between the musician and the instrument (Blum and Ahlers, 1994), sudden increases in practice time (Brandfonbrener, 1995), “radical changes in hand technique”

(Brandfonbrener, 1995), excessive joint postures (Kihira, 1995), overuse of the extremity (Fry, 1987), and “asymmetrical loading in the cervical spine” (Fry, 1989). Static awkward posture may potentially lead to fatigue (Quarrier, 1993; Hartsell and Tata, 1991).

In an attempt to determine the effect of design characteristics on left shoulder pain in violists, Blum and Ahlers (1994) investigated the design characteristics of the viola in detail. In this study, 311 violists were interviewed from a pool of 1432 string players. Reports of injury were less common (86% reported injury) in those playing smaller instruments (≤40 cm length) compared to those (92% reported injury) playing larger instruments. Injury incidence rate peaked with those playing instruments larger than 40 cm in length. In those musicians presenting with symptoms, the increase in injury incidence was attributed to increased reach with the left upper extremity, increased extension of the left elbow, hyper-extension of the left wrist, and supination of the forearm in certain fingering positions. Superimposed upon these awkward postures is the high incidence of disorders of the left rotator cuff, especially that of the supraspinatus muscle. Shoulder injuries were more common than disorders in other parts of the left upper extremity, with 18% of injuries attributed to the left shoulder in violists playing instruments less than 40 cm in length, and 25% of injuries attributed to violists playing instruments greater than 40 cm in length.

Bejjani et al (1989) stated that high levels of tension or a “whole arm technique” may contribute to upper limb muscular disorders, but no correlation was determined in their research on muscle activation in the forearm of violinists during vibrato. They were able to discern a reliable sequence of forearm muscle activation order amongst violinists performing standardized repertoire.

Philipson et al (1990) reported higher levels of average EMG activation in the upper trapezius, deltoid, biceps, and triceps muscles of “injured” professional violinists during the performance of standardized repertoire than in an uninjured group. Unfortunately, not much useful information can be inferred from the average EMG signal because it may be comprised of frequent fluctuations (frequent “passes” through several EMG amplitudes) through varying levels of muscle activation (frequent “passes” through several EMG amplitudes), or of a statically held contraction at a narrow level of fluctuation. This dynamic fluctuation, or lack thereof, in the EMG signal may explain the level of exposure of the muscle to features that are more related to risk, but the signal that they obtained does not reveal any useful information about the relative muscle exposure in the musical performance.

In a more recent study, Berque and Gray (2002) used a similar method of recording average EMG in injured and uninjured groups of violinists. They used a more sophisticated EMG normalization technique, as described by Mathiassen et al (1995), and a more reliable EMG electrode placement technique compared to that used by Philipson et al (1990). Philipson et al used the center of the line joining the C7 spinous process and the acromio-clavicular joint as the site of recording, whereas Berque and Gray used the point 2 cm distally along the same line. Mathiassen et al (1995), in a review of upper trapezius surface EMG recording studies in ergonomics, recommended that this is a more appropriate position since it is closer to the aggregation of motor end plates in the upper trapezius muscle. The site chosen for the reference electrode (C7 spinous process) was close to the area of EMG recording (upper trapezius) and there may have been some inadvertent recording of upper trapezius EMG at the site of the reference electrode. This may also have resulted in inadvertent muscle recording by the reference electrodes. This would result in sub-optimal control of the common mode rejection ratio of the EMG signal. Furthermore, the sample size used by Berque and Gray (10 subjects comprising 4 males and 6 females, 5 of whom were violists and 5 violinists) was small. Differences between groups (those with performance related medical disorders (PRMDs) and those without) demonstrated low levels of significance. There were significant between-group differences in Percentage Relative Voluntary Electrical activity (%RVE) (p=0.05). Pain free subjects recorded higher upper trapezius activity (9% RVE difference) than musicians with neck and shoulder pain (p=0.05). However, the authors summed the left and right upper trapezius %RVE in this test, thereby failing to discern side-to-side differences, or the impact of side-specific effects. They acknowledged that there were insignificant differences in the recruitment of these two muscle groups (p=0.265), but failed to note differences between the groups (injured and uninjured) with, “side” as a co-factor. Differences between the two groups, with degree of repertoire difficulty as a co-factor, were insignificant (p=0.169). Inferences about these two groups should be made with caution because of the small sample size and the addition of the left and right side data.

Recording of upper trapezius EMG from this location, as opposed to other portions of the muscle, is particularly important considering that this is the portion of trapezius that is most active in stabilization of the scapula, particularly in relation to the balance of this activation with serratus anterior (Johnson et al, 1994). Johnson et al used cadaveric study to elucidate the true mechanism of upper trapezius and appeared to dispel arguments that it generates an upward force directly on the scapula since its upper fibers attach to the clavicle. The middle fibers, which emanate from the nuchal line between C2 and C7 (and not individual spinous processes), radiate laterally to the spine of the scapula and help to stabilize the scapula. The bulk of the trapezius muscle emanates from C7 and T1 and these fibers attach to the spine of the scapula all the way to the acromion process and their action is to draw the scapula backwards or medially. These fibers therefore act to counter the upward rotation of the serratus anterior or the downward rotation of the levator scapulae.

Berque and Gray (2002), Philipson et al (1990) and Levy et al (1992) used average EMG as the dependent variable in upper extremity EMG studies in string players. Musicians interpret the same repertoire differently and express their interpretation of the music with dynamic movements in their upper extremities, the use of vibratory oscillations of the left elbow and wrist (flexion and extension) known as vibrato, and high and low force bow strokes to play more loudly or softly, amongst other features (Okner, 1997). Therefore the average EMG across subjects may not be truly representative of the exposure of the musicians to muscle use.

Blum and Ahlers (1994) cited the desire to play a larger instrument with a deeper, richer sound, as a potential risk factor for injury in violists. The viola is an instrument that looks similar to a violin but it is larger (longer and wider) and heavier. They suggested that performance with a larger viola made it difficult for the musician to use the right (bow) arm. Attempts to redesign the instrument have been unsuccessful for both sound quality and aesthetic reasons.

Brandfonbrener (1995) found that sudden increases in practice time was the most frequently reported precipitating factor with respect to the onset of focal dystonia amongst 58 musicians diagnosed with the disorder at a major metropolitan arts medicine facility. Kihira et al (1995) used an electrogoniometer to track the exposure of the wrists to excessive posture in violinists. They found that right wrist postures deviated more from neutral than the left side. However, Manchester and Flieder (1991) found that the incidence of right wrist injuries was far less (6/27) than amongst left wrist injuries (21/27).

Because of repercussions that may ensue, musicians are reluctant to report injuries (Ziporyn, 1984). Their concerns include the perceived effect that the report of injury may have on their grades, as well as the possibility that they may be omitted from a performance, or that the injury may require surgery resulting in permanent disability and extended loss of income. A recent pilot study that sought to recruit, “normal, healthy volunteer violinists and violists”, failed to recruit such a population (Reynolds and Ludewig, 2002). Six of the seven participants considered themselves, “normal”, and, “healthy”, yet it was evident after perceived disability evaluation (Shoulder Pain and Disability Index (Williams et al, 1995)) and findings of a physical examination that this was not the case.

Some musicians presented with right periscapular muscle pain and tenderness (tenderness and soft tissue changes to palpation of the levator scapulae insertion at the superior angle of the scapula (4/7 or 51%), and/or bilateral upper trapezius muscles (3/7 or 43%)), as well as abnormal resting scapulo-thoracic posture based on visual observation. Shoulder malalignment comprised downward scapula rotation, anterior tilting or medial rotation, or a combination of the above. This suggests that there is a pervasive perception in competitive musicians that these disorders are a normal consequence of performance at this level. The observations in this pilot study (Reynolds and Ludewig, 2002) are in agreement with views expressed by Ziporyn (1984). Therefore, there is the possibility that the injury prevalence amongst musicians that is reported in the literature is underestimated and that careful examination is required to determine the injured or non-injured status of these musicians in research that is performed to evaluate factors associated with injury.

Subacromial Impingement Syndrome

Subacromial Impingement Syndrome (SIS) is reportedly one of the most common causes of shoulder pain (Jobe and Jobe, 1983; Michener et al, 2003). SIS refers to the compression of soft tissue structures between the humeral head and the undersurface of the acromion process and/or the coracoacromial ligament. Soft tissue structures include the biceps tendon, the subacromial bursa, and the distal fibers of the supraspinatus and infraspinatus musculotendinous units, and impingement of these structures is referred to as *subacromial impingement*. It may also include impingement between the undersurface of the supraspinatus and/or infraspinatus muscle-tendon units and the glenoid process and/or glenoid labrum and this is known as *internal impingement*.

Researchers are not in agreement regarding the cause of subacromial impingement syndrome. Various features are purported to be associated with SIS, though not necessarily causally related, but in some cases may be associated in a compensatory capacity. These features may be summarily described as being related to motion abnormalities of shoulder components, such as the scapula, shoulder morphology (bony and soft tissue), muscular dysfunction, postural abnormalities, and soft tissue tightness.

Motion Abnormalities

Some trends in motion abnormalities have been identified using various motion analysis systems, including 2- and 3-dimensional (2-D and 3-D) motion analysis investigations. Ludewig and Cook (2000), using a 3-D system of motion analysis, found that subacromial impingement was associated with decreased scapula upward rotation at approximately 60 degrees of glenohumeral elevation in the scapula plane, and increased anterior tipping of the scapula at approximately 120 degrees in a comparison between subjects with subacromial impingement and those without. The findings of increased scapula downward rotation with arm elevation were supported by Endo et al (2001), and Su et al (2004) in subjects with a clinically determined diagnosis of subacromial impingement. Endo et al (2001), using a 2-D radiographic technique, and Lukasiewicz et al (1999), using 3-D projection angle methodology, also found that subjects with subacromial impingement had a tendency to show reduced posterior tilting in the scapula with arm elevation. Hebert et al (2002) found that increased internal rotation of the scapula during flexion at the glenohumeral joint was evident in those with impingement. They concluded that the scapula contribution to shoulder motion varies, depending on the motion (flexion or abduction), however, none of the other scapula motions was statistically significant in the SIS group for either motion. In the presence of rotator cuff tears, confirmed with magnetic resonance imaging, ultrasonography, or arthrogram, the scapula has been shown to upwardly rotate on arm elevation (Deutsch et al, 1996; Paletta et al, 1997; Graichen et al, 2001; Yamaguchi et al, 2000; Mell et al, 2001). Open MRI instrumentation assisted Graichen et al (1999) to establish that activation of the supraspinatus muscle at 90 degrees abduction resulted in narrowing of the subacromial space in subjects with subacromial impingement ($p<0.05$) and even more narrowing was seen in those with full thickness rotator cuff tears compared to healthy controls ($p<0.05$). This finding was not observed to the same extent in uninjured subjects. Compensatory increased upward rotation of the scapula has been artificially replicated using a block of the supraspinatus and infraspinatus muscles, thought to simulate full thickness tear of these rotator cuff muscles (McCully et al, 2006). Scapula upward rotation was thought to be a compensatory motion in all cases by Paletta et al (1997), since they found that this motion abnormality reversed after rotator cuff repair surgery.

The concept of abnormal rhythm between the scapula and the humerus with elevation was first described by Codman (1934) and was later described in more detail by Inman et al (1944). Inman et al (1944) postulated that the humeral to scapula motion ratio was 2:1. More recently, Doody et al (1970) found that this ratio varied with the degree of humeral motion and was 4:1 up to 30 degrees, and 0.8:1 after 80 degrees. Poppen and Walker (1976) suggested that abnormal ratios of scapula motion with elevation could contribute to impingement. Bagg and Forrest (1984) found that the ratio was 4:1 up to 80 degrees, and 0.7:1 thereafter. Johnson et al (2001) developed a 2-D inclinometer method that could reliably be used in the clinic to evaluate scapula upward rotation with humeral elevation and results were similar to those of Doody et al (1970). Similar inclinometric measurement techniques have been compared more recently to 3-D kinematic analysis, and results were found to be dissimilar to those of Doody et al (1970) in one instance (Borsa et al, 2003) and dissimilar in another (Watson et al, 2007). Variability in these studies probably relates to the 2-D methodology and systematic error in the methodology.

Therefore, it appears that the scapula contribution to arm elevation (either flexion or abduction) may depend on the integrity of the rotator cuff, the motion being performed, and the relationship of the movement of various bony components of the shoulder.

Morphology Abnormalities

The anatomy of the coracoacromial arch and the humeral head (Zuckerman et al, 1992), and aberrations in the morphology of the acromion (Farley et al, 1994; Bigliani and Levine, 1997), have also been linked to SIS. Zuckerman et al (1992) found a significant correlation between narrowed subacromial space and the incidence of rotator cuff tears ($p<0.001$). Similar findings were also evident for acromial tilt ($p<0.01$) and coracoacromial ligament length ($p<0.001$), with injured subjects having a shorter ligament than uninjured subjects. Farley et al (1994) found no statistical association ($p<0.078$) between those with supraspinatus tears and type III acromion process morphology, but they did report a statistically significant relationship between those with supraspinatus tears and a thickened coracoacromial arch ($p<0.01$), and subacromial enthesophytes ($p<0.02$).

Muscular Dysfunction

Muscular control of scapula kinematics is complex and multifactorial, considering all the muscles that either stabilize and/or move the scapula in varying positions, and which generate and control various motions. The balance between upper trapezius and serratus anterior has been cited in several studies as being critical to the movement and position of the scapula, but particularly with elevation of the arm (Johnson et al, 1994; Ludewig and Cook, 2000, Lin et al, 2005), or with sporting activity, such as with overhead athletes (Cools et al, 2007). Cools et al (2007) found that the upper trapezius was significantly more active in those with impingement with Isokinetic arm abduction and external rotation ($p<0.001$), and that the upper to lower trapezius, and upper to middle trapezius ratios were significantly higher in the patient population ($p<0.001$) compared to non-injured subjects, as well as when injured shoulders were compared to non-injured shoulders in the injured group.

Ludewig and Cook (2000) demonstrated that participants with SIS demonstrated decreased serratus anterior ($p<0.05$), and increased upper and lower trapezius electromyographic activity than those without impingement syndrome. This suggested that those with SIS over-recruited the upper and lower trapezii and failed to adequately recruit the serratus anterior, thus allowing the scapula to rotate downwards, tilt forward (or fail to tilt backwards sufficiently) and rotate medially during motion, compared to those without SIS.

The timing of muscular activation in periscapular muscles has also been cited as a significant contributor to abnormal scapula kinematics (Cools et al, 2003): overhead athletes with impingement showed significant latency in middle and lower trapezius activation compared to healthy controls with a “drop-arm test” where the arm is held at 90 degrees abduction and then unexpectedly dropped. However, the researchers admitted that they could not determine whether the latency was causative or compensatory in the experimental group. This variability is also seen in freestyle swimmers with shoulder impingement, although, as with pain, causal versus compensatory strategy is indeterminable (Wadsworth and Bullock-Saxton, 1997).

Burkhart et al (2003) also indicated that scapulothoracic dyskinesis suggested the presence of subacromial pathology.

Soslowski et al (2002) has proposed, using an animal model, that a combination of eccentric overload of the rotator cuff and reduced available subacromial space, or eccentric loading alone, contribute to SIS. SIS is usually the consequence of cumulative trauma rather than acute trauma, and is most likely to be the result of scapulo-thoracic movement abnormality, coupled with rotator cuff disease (Neer, 1983).

Soft Tissue Tightness

Muscular or capsular tightness reportedly has significant effects on scapulothoracic kinematics and static posture. Borstad and Ludewig (2005) identified significantly decreased scapula posterior tilting and increased medial rotation with arm elevation in symptom free individuals with tight pectoralis minor. Kibler (1998) theorized that internal rotation of the glenohumeral joint in an elevated position would result in abnormal scapula kinematics, mostly resulting in “protraction” of the scapula on the thorax. Posterior glenohumeral capsule tightness has also been shown to increase anterior tilting in the scapula in a fully internally rotated glenohumeral joint with 90 degrees of abduction and flexion compared to individuals with no posterior capsular tightness (Borich et al, 2006).

Postural Abnormalities

Increased thoracic curvature may also be linked to abnormal scapula position and kinematics. Simulating increased kyphosis (slouching) with simultaneous arm elevation results in reduced scapula upward rotation and posterior tilting, and reduced internal rotation and elevation (vertical translation) (Kebaetse et al, 1999). Increased thoracic kyphosis, as seen in women with progressive aging, has been linked to increased scapula anterior tilting and internal rotation (Culham and Peat, 1993), motions which have been shown to reduce subacromial space (Michener et al, 2003).

In summary, subacromial impingement syndrome is a common and complex condition, and the pathomechanics of its cause and resultant compensatory strategies is controversial. Since it is likely that violinists perform in positions that have been shown to be associated with subacromial impingement (humeral elevation, internal rotation, and scapula protraction), particularly a position that at times resembles the Hawkins-Kennedy impingement test (Reynolds and Ludewig, 2002), it appears likely that assessment of the three-dimensional kinematics of the right shoulder in this population is necessary in determining a possible correlation between shoulder impingement and performance with a violin.

Exposure Variation Analysis (EVA)

Many occupations involve work that is not forceful in nature, but rather characterized by periods of sustained low force activity, often repetitive in nature. Quantification of the exposure of the worker to this activity, and its physiological sequelae, has been attempted in several different ways, including observational techniques, epidemiological analysis, and on-site field experimentation utilizing electromyography and/or goniometric instrumentation. Several such methods have been proposed, including the amplitude probability distribution function (APDF) proposed by Jonsson (1978), the contract frequency analysis (CFA) proposed by Winkel and Bendix (1984), and the exposure variation analysis (EVA) proposed by Mathiassen and Winkel (1991).

The amplitude probability distribution function (APDF) (Jonsson, 1978) was introduced as a means to grade myoelectric activity during continuous work into semi-arbitrary force categories. This relies on the proportional and positive relationship between myoelectric activity and force production. The myoelectric activity of the muscle (EMG) is recorded over a normal work period (lasting hours), full-wave rectified, low pass filtered, and then compared to test contractions against known forces (to acquire a more linear relationship between force and myoelectric signal, since fatigue will interfere with this). The relative curve (representing % maximum voluntary contraction or %MVC) is then tilted 90 degrees and amplitudes are sorted cumulatively from lowest to highest to estimate the lowest (static) to the highest levels of work, as well as the median level of work over the entire work period. This method does not take into consideration the frequency of muscular contractions and therefore the contract frequency analysis was developed (Winkel and Bendix, 1984). The CFA represents the frequency with which the smoothed EMG signal crosses predetermined amplitude levels, representing “load levels” if one assumes a linear relationship between EMG and force. The outcome is a frequency/force index and an estimate of time spent at each of the load levels during the total time under investigation.

Exposure Variation Analysis (Mathiassen and Winkel, 1991) was introduced as a superior alternative to APDF and CFA. Neither of the two preceding methods of expressing occupational exposure is ideal. The APDF does not reflect changes in cycle time and the CFA does not reflect changes in duty cycle, and neither of the two methods reflects changes in the distribution of load on a real time scale (Mathiassen and Winkel, 1991). A combination of these two data reduction techniques would allow for the assessment of time that the myoelectric signal spends at a particular amplitude, and the frequency with which this signal passes through the various pre-determined amplitude divisions. Processing the signal twice, as would be necessary if using the APDF and CFA methods, makes this a lengthy and cumbersome process. In addition, the total work time is omitted as a factor in the analysis and therefore the entire signal needs to be processed in this way, making for a very lengthy period of analysis of a large data set. These techniques, if used in isolation, are sub-optimal for assessing exposure when concerned with the composite of these measures of exposure.

Exposure variation analysis (EVA) is a data reduction technique that takes the cycle time and the duty cycle into consideration simultaneously, and represents the total work time in an array defined by various amplitude levels and time duration parameters. The values of the, “bins”, or cells in the entire array are proportions of the entire work period and therefore sum to 1. Mathiassen and Winkel (1991) suggest that the technique is more representative of physiological variations than the CFA or APDF, therefore adding to its utility in the identification of exposure variables in the workplace. In addition, they suggest that muscular load levels be represented logarithmically (log base 2) since long duration and high load (percentage of maximum voluntary contraction, or %MVC, or percentage of maximum voluntary electrical activity, or %MVE) situations are rare in high repetition industries under investigation (textile manufacturing and electronics assembly). EVA does not satisfactorily depict total time duration for work tasks, neither does it allow for the temporal assessment of variables under investigation (Mathiassen and Winkel, 1991).

EVA has been successfully used to establish the efficacy of ergonomic interventions in various assembly (Mathiassen Winkel, 1996; Bao et al, 1997), automobile assembly (Hägg et al, 1997), service (Jansen et al, 2001), and construction (Anton, 2002 b) industries. The method has enabled researchers to differentiate between muscle activation level or joint range of motion, and duration spent at such activation levels or joint ranges (repetition) (Hägg et al, 1997, Jensen et al, 1999) in office work situations.

Mathiassen and Winkel (1996) investigated upper trapezius EMG at different work paces (120% of methods time measurement (MTM) pace, or 120 MTM, and 100 MTM) in a simulated assembly line experiment. They found that reducing the pace of work resulted in a significant decrease in repetitiveness (p=0.02) and in lower and more variable amplitude. Interestingly, they found significant reduction in amplitude from 120 MTM compared to 100 MTM for the entire day using the APDF data reduction technique (p=0.03), whereas they failed to show this with the EVA technique (p=0.09). They attributed this to having tested too few subjects (n=8) to show enough of a change. However, the APDF, as mentioned above, does not describe repetitiveness and therefore has limited use in this regard.

Bao et al (1997) used EVA data reduction techniques to detect differences in right upper trapezius and infraspinatus exposure between Swedish and Chinese assembly line workers. Despite the superior design of the Swedish workstation, more repetitiveness was seen in the upper trapezius and supraspinatus muscles in Swedish compared to their Chinese counterparts (p<0.01), and their upper trapezius and infraspinatus amplitudes were greater than those of the Chinese workers. They attributed this to a faster production rate in the Swedish workers, probably because of improved production engineering.

Hägg et al (1997) used EVA data reduction methods to compare flexor carpi radialis and extensor carpi radialis longus EMG exposure, and wrist flexion/extension and radial/ulnar deviation angular data in 20 (female n=2, male n=18) asymptomatic assembly line workers in workstations with low and high hand symptom incidence. Logarithmic scaling was used for EMG amplitude and time duration as recommended by Mathiassen and Winkel (1991) and linear scaling was used for angular data. This evaluation technique enabled the detection of differences between flexors and extensors in terms of static versus dynamic activation, as well as simultaneous identification of the amplitude of contraction. The same was true in the identification of angular exposure. Workers performing tasks where a high prevalence of symptoms had been detected operated with greater ulna deviation and with higher angular velocity in the coronal plane (ulna and radial deviation) than workers who performed tasks at workstations with low symptom prevalence.

Jensen et al (1999) used EVA methods to detect differences in upper trapezius activation in the dominant arms of production workers (metal can production) and the mouse arms of computer aided design (CAD) workers. Production work resulted in a more dynamic upper trapezius activation (higher repetition) whereas CAD work was more static and of lower amplitude.

Few of these studies have commented on the reliability and validity of the technique. This may be due in part to problems associated with the statistical analysis techniques used to determine differences between variables under investigation. Multivariate analysis of variance (MANOVA) has been used in previous EVA studies (Bao et al, 1997, Mathiassen and Winkel, 1996, Hägg et al, 1997), however the independence assumption is violated since data bins are not independent of one another. The data array represents one hundred percent of the work performed: if one bin value increases, another or others in the array must decrease. Furthermore, as the measurand (either full-wave rectified and smoothed EMG signal or kinematic signal) moves from one EVA amplitude level to the next, it is assumed that the time spent in each of these levels is more correlated than with those in more removed amplitude levels. Mathiassen and Winkel (1996) proposed that eliminating one row in the array would help to circumvent this problem. In addition, the studies that have investigated ergonomic intervention efficacy have been performed with small sample sizes.

Jansen et al (2001) and Anton (2002 b) used alternative methods to analyze differences between EVA arrays in occupational settings using data-logger technology. Jansen et al (2001) used a two-step regression method to assess differences between spinal range of motion (rotation in the sagittal plane) arrays in workers performing pushing tasks. Logistic dummy variables were assigned to represent cells in the collection of arrays generated during the study. The authors used statistical methods that assumed that transition from one time interval to the next was continuous and therefore that adjacent bins were more closely correlated and that bins further removed from one another were less correlated. This assumption is erroneous since the intervals are created arbitrarily to represent the time that the electro-goniometer signal spends within a particular amplitude level. There is no reason therefore to justify that these arbitrary time intervals would be correlated. Adjacent amplitude bins are more closely correlated since they do represent temporal transition from one range of motion amplitude level to another, and therefore from one bin to another in the final EVA array. Jansen et al used a complex Beyesian log-linear regression model to identify differences between arrays (Jansen et al, 2001). The cells in the EVA array represent percentages of time spent at various, “intensity” levels (in this case complex spinal rotation in the sagittal plane) and time durations. If the value of one bin increases, one or more of the other bins in the array must decrease, therefore indicating that they are not independent of one another. Removing data in a column or row does not adequately address the violation of independence since amplitude bins are more correlated with adjacent than with, “distant” bins in the array, yet adjacent time bins are not correlated.

Anton (2002 b) used a two-way mixed-effects repeated measures ANOVA to assess differences between clusters in EMG EVA arrays (CEVA) in operating engineers and mechanics. Two columns and a row of data in each array were eliminated and the remaining bins/cells defined by these borders were added together to create six clusters within the arrays. These comprised high intensity-prolonged duration, high intensity-short duration, moderate intensity-prolonged duration, moderate intensity-short duration, low intensity-prolonged duration, and low intensity-short duration clusters with data representing the sum of bins within the cluster. He then tested for normality within the clusters to ensure that they were normally distributed. Log, natural log, and inverse transformations of the data were used in cases of non-normality to transform data. Main effects of trade and EVA exposure category, as well as interactions between trade and exposure category, were assessed using general linear models.

Neither one of these two methods is ideal. The methods used by Jansen et al (2001) and Anton (2002 a and b) failed to account for the fact that adjacent within-column bins (electrogoniometer levels) in the array were more correlated than distant within-column bins, and that adjacent within-row bins (time intervals) were not correlated with one-another. Anton removed potentially valuable rows and columns of data to create clusters of data. Jansen et al used an arbitrary method of clustering data into various groupings.

There is no, “gold standard” of work exposure with which to compare EVA, making the determination of criterion validity difficult. In a recent study to assess the reliability of EVA as a method of quantifying exposure, Anton et al (2002 a) used a repetitive gripping task with standard force levels and pre-determined duty cycles. They found, using a clustered mixed-effects model, that cluster EVA (CEVA) had high reliability (ICC 0.82). However, row and column data was discarded in this study, possibly resulting in the loss of important information that may have been useful in exposure analysis. Researchers need to rely on observation of the task and the EVA array to make inferences about the construct validity of EVA.

Reynolds and Ludewig (2002) recently used a logistic auto-regression model to investigate similarities in kinematic (scapula external/internal rotation about the thorax, scapula upward/downward rotation about the thorax, scapula anterior/posterior tilting in relation to the thorax, humerus elevation in relation to the scapula, humeral horizontal flexion/extension in relation to the scapula, and humeral internal/external rotation in relation to the scapula) and EMG (right and left upper trapezii and right and left serratus anterior) variables between first and second performance of work tasks for fast and slow musical repertoire. An exchangeable correlation structure of compound symmetry for subjects within cells (EVA cells/bins of which there are 49) across their four trials (fast and slow speeds performed twice each) was used. This method assumed that bins in the array were correlated but it ignored the pattern of correlation that may exist between bins. It did not rely on the elimination of potentially valuable data to achieve this, as happens when rows or columns of data are eliminated to avoid violating the independence assumption. Similarity between trials for each instrument was observed ($p>0.05$), which indicated that the EVA technique was a reliable method in the assessment of the exposure of the musician to kinematic shoulder motion variables, and trapezius and serratus anterior muscle activation. Differences between the slow and fast repertoire, as well as between violin and viola groups for each work task, were also assessed in this manner and were found to be well correlated.

The results of this pilot research suggest that the EVA method has good repeatability in determining the exposure of the musician to kinematic and electromyographic factors, in this case upper trapezius and serratus anterior exposure, and 3-dimensional scapulothoracic and glenohumeral kinematic exposure. This indicates that the EVA methods may be useful in further determination of exposure of these musicians to performance risks involving muscle activation and kinematic variables.

Use of EVA data reduction methods will enable this investigator to simultaneously evaluate the exposure of violinists to muscle activation level and repetition, and to adverse shoulder motion. Because it may be anticipated that violinists with right shoulder discomfort will demonstrate longer periods of static activity in both EMG and kinematic variables, those musicians with little or no discomfort will demonstrate more variability in muscle activation (in terms of both activation level and time duration) and shoulder motion. The high level of precision and anticipated repeatability of the tasks performed by orchestral violinists will allow the development of repeatable EVA patterns for both fast and slow repertoire, as was demonstrated using a small sample population in recent pilot research (Reynolds and Ludewig, 2002). It is anticipated that significant correlations exist between abnormal shoulder kinematics (posture that deviates markedly from neutral and which is more static in nature, i.e. static, awkward posture) and outcome variables that indicate a higher level of disability and dysfunction, and also between abnormal muscle activation (high levels of activation and static contraction, indicating sustained higher force contractions) and outcome variables that indicate a higher level of disability and dysfunction. Moreover, these correlations may be useful in assessing the efficacy of interventions designed to normalize shoulder posture, vary posture durations, and vary muscle activation.

Despite its drawbacks (mostly related to statistical analysis), EVA is thought to be a useful exposure analysis tool for simultaneously evaluating several risk factors. Furthermore, it will greatly assist the identification of performance related risk factors and the assessment of abatement strategies for violinists and other worker populations.

Significance

The proposed study therefore aims primarily to determine the relationship between right scapulothoracic and glenohumeral kinematic exposure variation analysis (KEVA) patterns (range of motion, and time duration spent at a particular range of motion), and upper trapezius and serratus anterior electromyography exposure variation analysis

(EEVA) patterns (muscle activation level, and time duration spent at activation levels) in violinists with and without subacromial impingement syndrome.

Secondarily, the effects of pre-evaluation outcome variables, such as instrument dimensions, anthropometric dimensions, questionnaire data, and physical examination outcomes, on right shoulder kinematic and electromyographic variables (KEVA and EEVA) will be assessed in violinists with and without subacromial impingement syndrome.

It is anticipated that quantitative assessment of these exposures with respect to various performance characteristics (repertoire performance at different speeds) may advance the understanding of three-dimensional scapulothoracic and glenohumeral kinematic exposure, and upper trapezius and serratus anterior muscle exposure during musical performance. It is also anticipated that these methods may provide the foundation for future research into therapeutic interventions aimed at the abatement of these exposures.

Quantification of the exposure of the violin musician to kinematic and muscle activation level, each in relation to repetition, is likely to assist health care practitioners in preventing shoulder and neck musculoskeletal disorders, since these variables may explain the prevalence of these disorders in violinists. Furthermore, it is anticipated that this will also enhance the awareness of these disorders in the music field, therefore helping to avert the onset of right upper trapezius pain in younger string musicians. Knowledge of this information may also assist music teachers in the selection of appropriate instruments and repertoire for their students.

Stature is proportional to anthropometric dimensions, including factors such as arm length and hand size (Winter, 1991, pages 51-52). Therefore, cognizance of this may help to prevent students from taking on an instrument that is not anthropometrically suited to them. Furthermore the progression of a student to more difficult repertoire before optimal techniques are learned on basic repertoire may be avoided with improved knowledge regarding their exposure to various kinematic and EMG variables in the shoulder. This may have widespread impact on the music student population and significant impact on injury prevention.

Equally, it is anticipated that EVA repeatability will be confirmed in this highly repeatable and precise occupational task. This will serve to qualify EVA as a reliable technique to further analyze violinists and other instrumentalists. This is important, as it will ensure future use of a technique ideally suited for the purpose of determining the interaction of co-existing risk factors in ergonomics.

CHAPTER 3

EXPERIMENTAL METHODS AND DESIGN

General Methods

Participants

Fifty violinists (25 with right-sided subacromial impingement syndrome and 25 controls) with at least 15 years of playing experience were sought to participate in this study. No minors were recruited. It is common for musicians to commence playing as young as 4 years old, so musicians as young as 18 were deemed appropriate for this study as it was considered likely that they would possess the necessary skill to perform the experimental musical repertoire with sufficient proficiency.

University of Minnesota Institutional Review Board (IRB) approval was acquired before commencing with data collection, and all musicians were required to comprehend and sign an informed consent document (Appendix A) before being admitted to the study. Comprehension of the data collection process and informed consent procedure were determined using a questionnaire that was developed previously and used in pilot research (Reynolds and Ludewig, 2002).

Exclusion Criteria

Musicians with metal implants were excluded from the study so as not to distort the electromagnetic signal from the kinematic data collection apparatus. Only those who were autonomous agents (those able to demonstrate sufficient comprehension of the research objective, free of coercion, and who were at least 18 years of age) were admitted to the study.

Inclusion Criteria

Violin musicians over the age of 18 who could satisfactorily perform the required musical repertoire, and who willingly signed consent were admitted to the study. Participants were divided into two groups, injured (those with right shoulder subacromial impingement syndrome (SIS)) and uninjured. Participants were grouped into experimental (positive for SIS) and control (negative for SIS) groups for this study as follows:

1. The participant reported having experienced right shoulder pain within 2 weeks prior to participating in this study.
2. The participant tested positive on at least two of the five impingement tests, namely the Hawkins-Kennedy test, Neer’s test, Jobe’s Test, Speed’s test and the Painful Arc test.
3. The participant reported shoulder pain on manual muscle testing of external rotation, abduction or internal rotation and this pain report coincided with the impingement sign(s) that were positive in terms of structure involved in impingement.

Participants were excluded if they presented with two or more impingement signs and yet did not report pain in the 2 weeks prior to the date of data collection, or if they presented with two or more impingement signs, yet had no pain on manual muscle testing. This was found to be the case with 3 participants, numbers 2, 17, and 40.

Questionnaires

Participants completed various questionnaires that were used to evaluate information about them.

Demographics and Performance

After detailed explanation of the study and the signing of the informed consent document, participants completed a comprehensive demographic and basic health questionnaire (Appendix B): this questionnaire was used to acquire the participant's demographic information, as well as age, weight, height, gender and hand dominance. With respect to musical performance, this questionnaire also acquired information regarding the following:

1. Years of playing experience,
2. Number of hours spent practicing per week,
3. Number of hours spent performing per week,
4. Number of hours spent teaching per week,
5. Level of performance (student, amateur, professional).

The participant also completed a section regarding past medical history.

Perceived Function

Participants completed the Shoulder Rating Questionnaire (L'Insalata et al, 1997) to determine their comfort level and perceived rating of function with respect to the right shoulder. This form of evaluation is particularly useful in that it is inexpensive, and the results can be compared with the many subjective assessments that have been published on these populations. The Shoulder Rating Questionnaire (SRQ) has been shown to be a reliable and valid tool to assess perceived shoulder function, and the questionnaire was found to be responsive to various diagnostic groups (L'Insalata et al, 1997). Furthermore, the criterion validity of the SRQ was found to be well correlated with the Arthritis Impact Measurement Scales 2, a questionnaire evaluation that has proven to be a reliable and valid index of health status (L'Insalata, et al, 1997). The SRQ was also found to have good criterion validity, with subject's scores marked for improvement correlating well with lower scores on the questionnaire, indicating lower perceived function, or more impact on function due to pain. Lastly, the SRQ was found to have excellent internal validity (Cronbach Alpha 0.86) (L'Insalata, et al, 1997).

The results of such questionnaire evaluations have been shown to be reliable with respect to inter-test consistency (Franzblau et al., 1997), as well as in direct observation and instrumented measurement (Baty et al., 1986). Franzblau et al (1997) indicated that research participants displayed good to excellent reliability in identifying the presence or absence of upper extremity symptoms. They also displayed good test-retest reliability in identifying the severity of upper extremity symptoms, as well as the causal relationship to a work station or activity. Research has also shown that the perceived ability of workers is a more reliable indicator of their ability to work than observed or measured parameters (Bigos et al, 1986).

Perceived Pain

Participants completed a visual analog pain scale to assess the pain they were experiencing in the right shoulder just prior to data collection. The questionnaire comprised a 10-cm long vertical visual analog scale (Appendix C) between the extremes of, “No Pain at All”, at the bottom of the scale and, “Pain as Bad as it Could Be”, at the top of the scale. The result was determined by measuring the metric distance from the base of the scale to the line that the participant had drawn.

Musical Instrument Evaluation

The participant’s violin was evaluated with respect to the following:

1. Overall length (base of the instrument to the tip of the scroll) measured in millimeters using a cloth tape measure. See Figure 3.1 below.
2. Weight (as measured with the *PinchTrack*™ pinch gauge (Appendix G.4., see figure 3.2 below), JTECH Medical Industries, Salt Lake City, UT, USA) measured in kilograms. The *PinchTrack*™ was calibrated to a standard 4.53 kg (9.97 lbs.) weight prior to each participant’s evaluation.
3. Bridge to scroll length measured in millimeters (this represents the length of the actual strings that the bow is drawn across during performance) (see Figure 3.1 below).
4. Bridge height measured in millimeters using a cloth tape measure, (see Figure 3.4 below).

5. “Active neck height” (the distance from the bottom of the shoulder rest to the top of the chin rest) measured in millimeters (see Figure 3.3 below). This is referred to as the, “Active Neck Height” as this is the height of the musician’s neck while the instrument is being played and may vary in other situations. This is also a critical measurement as indicated by Okner (1997),
6. Bow length (length of the bow “hairs”) measured in millimeters using a cloth tape measure (see Figure 3.5 below).

The same tape measure was used for all instrument length dimension measurements and all measurements were performed by either the primary investigator or an assistant who was present for most data retrieval sessions.

Musicians vary in stature and they play instruments that vary in size, as well as in the dimensions listed above (Okner et al, 1997). It is possible that these differences may impact injury incidence and predisposition since it has been suggested that in their quest for a richer or deeper sound, they may choose to play larger instruments (Blum and Ahlers, 1994). However, this trend is more prevalent in violists than violinists. Therefore, no between-group differences were anticipated in this study.

Physical Examination

Participants underwent a physical examination during which various outcome variables were assessed. Posture was examined, and abnormalities in scapulothoracic alignment were visually inspected and recorded. Specifically, scapulo-thoracic posture was observed for the presence of scapula anterior tilting (evidence for this was indicated by a prominent inferior angle of the scapula in relation to the thorax), scapula internal rotation (evidence for this was indicated by a prominence of the medial border of the scapula in relation to the thorax), and scapula downward rotation (evidence for this was indicated by rotation of the medial border of the right scapula past the vertical in a clockwise direction). These postural observations were recorded as either present or absent (binary data) and were correlated with resting posture in the seated position, assessed using three-dimensional kinematic measurement prior to musical performance.

The participant was then tested for right subacromial impingement syndrome (SIS) using various impingement tests namely the Neer's test (Neer, 1983), the Hawkins-Kennedy test (Calis et al, 2000), Jobe's Test (Jobe and Jobe, 1983), Speed's test (Calis et al, 2000), and the Painful Arc Test (Calis et al, 2000).

The participants' pain response to manual muscle testing techniques for external rotation, abduction and internal rotation were evaluated. Positive tests were indicated by report of pain or increased pain in the motions tested, compared to a zero-load or resting status in the muscle group.

Range of motion tests were performed on both shoulder joints using a digital goniometer (Appendix G.2) (*RangeTrack*™, JTECH Medical Industries, Salt Lake City, UT, USA) in accordance with methods recommended by the American Medical Association (AMA) *Guidelines to the Assessment of Permanent Impairment,* 5th Edition (AMA Guides, 2001). Shoulder flexion, abduction, external rotation and internal rotation motions were measured for both shoulders. The RangeTrack instrument was calibrated prior to each participant's data collection. The instrument was found to have good repeatability (0.690%), hysteresis (0.690%) and linearity (-0.164%), and has a measured accuracy of

–1.146 to –0.243% during full-scale calibration through 120.65^o (Reynolds and Ludewig, 2002) (Appendix F).

The participants' minimum thoracic kyphosis angle was measured in the neutral standing position using dual digital inclinometers (*Dualer*™, JTECH Medical Industries, Salt Lake City, UT, USA) according to methods recommended by the American Medical Association (AMA) *Guidelines to the Assessment of Permanent Impairment,* 5th Edition (AMA Guides, 2001). The Dualer inclinometers were calibrated prior to data collection for each participant. The *Primary* inclinometer was aligned vertically in the sagittal plane at the T1 spinous process and the *Secondary* inclinometer was aligned vertically in the sagittal plane at the spinous process of T12. Participants were instructed to stand up as straight as possible and a single reading was recorded once they had remained in a static erect posture for at least 2 seconds. The instruments were found to have good repeatability (1.404%), hysteresis (2.105%) and linearity (0.691%) and had a measured accuracy of -0.814 to 0.825% during full scale calibration through 119.36 degrees (Reynolds and Ludewig, 2002) (Appendix F). Differences in kyphosis angles were evaluated between the injured and uninjured groups, since research has suggested that increased thoracic kyphosis may be related to the incidence of subacromial impingement (Culham and Peat, 1993; Kebaetse et al, 1999)

Electromyography Data Collection

The skin at the mid right upper trapezius, lower digitations of right serratus anterior, and the right distal antero-medial tibia was thoroughly cleaned with 70% rubbing alcohol until erythematous so as to reduce skin impedance. Pre-amplified (active) silver-silver chloride electromyographic (EMG) electrodes (Therapeutics Unlimited, Iowa City, IA, USA) were affixed in line with muscle fiber orientation to the right upper trapezius (RUT) and the lower digitations of the right serratus anterior (RSA) muscles using double-sided tape. The Therapeutics Unlimited active electrode apparatus has a 2 cm inter-electrode distance and an onsite gain of 35. The upper trapezius electrode was positioned according to methods described by Mathiassen et al (1995): the midpoint of the line joining the spinous process of C7 and the acromioclavicular joint was determined and the electrode was centered 2 cm distal to this point. The serratus anterior electrode was positioned according to methods described by van der Helm (1995): the lower digitations were palpated and care was taken to exclude fibers of the lattissimus dorsi and pectoralis major muscles. The electrode/skin interface was filled with EMG contact gel in a manner that eliminated the presence of bubbles, which serve to interfere with signal quality. A self-adhesive, “Red-Dot”, reference electrode (3M Corporation, Minneapolis, MN, USA) was placed over the right antero-medial distal tibia and provided differential amplification (input impedance >15MΩ at 100Hz) with a common mode rejection ratio of 87 db at 60 Hz (Therapeutics Unlimited, Iowa City, IA, USA). The gain was adjusted in each EMG channel to optimize the signal-to-noise ratio without saturating the signal: participants were instructed to contract the muscle in question against manual resistance provided by the investigator, and the gain was adjusted, based on observations of the signal on the oscilloscope and a light emitting diode (LED) that indicated signal saturation. Raw myoelectric signals were sampled at 1000Hz during the performance of rest, relative voluntary electrical activity (RVE), and music performance activities. Electromyographic data collection was synchronously recorded with kinematic data. The investigator observed the signal LED throughout all data collection to ensure that no signal saturation occurred at any time.

Raw EMG signals were sampled at 1000 Hz to avoid aliasing error, high pass filtered (20Hz), and analog-to-digital (A/D) converted using a 12-bit analog-to-digital (A/D) converter (Measurement Computing, Middleboro, MA, USA) and stored on a customized personal computer (Innovative Sports Training, Chicago, IL, USA) for later analysis. Raw signal quality was monitored on an oscilloscope (Tektronics, Wilsonville, OR, USA) during the experimental protocol and the oscilloscope was continuously monitored for signs of interference from the kinematic tracking apparatus transmitter and signal saturation. Three built-in notch filters (Innovative Sports Training, Chicago, IL, USA) were used to reduce any interference from the electromagnetic transmitter, or other interference sources in the laboratory. The notch filters were calibrated before each participant's data collection. These filters were tested during previous research study (Reynolds and Ludewig, 2002) and were found to adequately reduce the interference from the transmitter. There did not appear to be any noticeable interference from the transmitter beyond 25 cm. Care was taken to ensure that the participant remained in position so that the EMG electrodes were no closer than 25 cm and no further than 76 cm from the transmitter.

The raw EMG signals were digitally root-mean-square (RMS) processed using a 100 ms time constant (Mathiassen and Winkel, 1991, Jensen et al, 1999) and saved to a personal computer (Hewlett Packard, Palo Alto, CA, USA) for later analysis. This time constant was similar to that used by other researchers (Mathiassen et al, 1991; Hägg et al, 1997; Jensen et al, 1999). The data analysis planned for this experiment was not reliant on the frequency detail that would be afforded by a shorter time constant, and this resulted in a slightly smoother RMS signal for analysis. The signals were then digitally re-sampled at 100 Hz to facilitate exposure variation analysis (EVA) processing with a smaller data set. Since the signals had already been filtered and RMS processed, no substantial variation in repetition or amplitude was lost and the 30-second period of work sampled at 1000 Hz (30,000 data points) was essentially identical to that sampled at 100 Hz (3,000 data points) (Reynolds and Ludewig, 2002).

The EMG signal from each muscle was normalized to the relative voluntary electrical (RVE) activity of the muscle, acquired during the performance of a standardized activity, as recommended by Mathiassen et al (1995). The activity for the trapezius comprised holding both arms straight and horizontal in 90^o abduction while supporting a 0.91 kg weight wrapped around each wrist in the standing posture. The participant maintained this position for 7 seconds and the middle 3 seconds of 3 such contractions were averaged (the initial and final 2 seconds were eliminated); the median of this averaged sample of data was used as a representation of the upper trapezius RVE ($utEMG_{RVE}$). The participant was given a 2-minute rest with arms resting at the sides between each contraction to minimize the possible effects of fatigue.

Many different techniques of recording RVE have been used, and those that are recommended (Mathiassen et al, 1995) have been used by Berque and Gray (2002). The participant is instructed to elevate both arms to 90 degrees abduction with a 1-kg weight in each hand for 10-seconds while EMG recording takes place. In pilot research in preparation for this study, Reynolds and Ludewig (2002) required participants to perform the same technique with no weight in the hand as recommended by Mathiassen et al (1995) and found this technique resulted in a high degree of variability in the measured EMG. In some cases, the resting EMG value (EMG recorded with the participant seated and relaxed) was higher than the RVE EMG value, resulting in negative normalized EMG for EVA creation. Participants were noted to recruit the upper trapezius at different levels in relation to performance muscle recruitment and this was only realized in retrospect during the above-referenced pilot study. Hence, the method described above, with the addition of the 0.91 kg weight wrapped around the wrist, is regarded as being preferable, since it was considered more likely that this activity would produce a higher level of upper trapezius EMG compared to that acquired at rest, and the task was unlikely to cause excessive strain for the participant.

Serratus anterior RVE EMG was acquired with the participant seated in a high-backed nylon chair with the shoulder flexed to 90-degrees in the sagittal plane. A force transducer (*GripTrack*™, JTECH Medical Industries, Salt Lake City UT, USA, Appendix G.3) was brought to rest against the dorsum of the participants' proximal phalanges of the right hand with the hand held in a "fist", the shoulder flexed to 90 degrees, the elbow extended fully and the forearm in neutral pronation. The force transducer was secured in this position in a custom fabricated arresting jig and the participant rested the entire right upper extremity on the jig while performing a shoulder protraction activity so as not to activate the upper trapezius on the right side. The participant exerted a 4.55 kg shoulder protraction force against the transducer for 7 seconds, which he/she controlled with visual observation of a force read-out on a notebook computer screen (Dell Latitude personal computer, Dell Corporation, Round Rock, TX, USA). The participant was instructed in correct use of the serratus anterior for this task and the investigator ensured that the participant did not lean forward while exerting force against the transducer. The middle 3 seconds of each of the 3 contractions were averaged (the initial and final 2 seconds were eliminated). The median of this averaged sample of data was used as a representation of the serratus anterior RVE ($saEMG_{RVE}$). Three such contractions were re-recorded with a 2-minute rest between each contraction, with the participant resting in a seated posture with the upper extremity resting on the jig to minimize the possible effects of fatigue.

Resting EMG activity was acquired in both muscles during 7 seconds of rest. Arms were resting in complete relaxation across the participant's thighs while in a seated posture, similar to methods used by Mathiassen (1995). The median of the middle 3 seconds of this period were representative of the resting EMG ($utEMG_{Rest}$ and $saEMG_{Rest}$). The initial and final 2 seconds of the rest time were eliminated. The participant's normalized EMG for the performance tasks (performance of fast and slow repertoire) was therefore expressed as a function of the RVE and resting EMG in each muscle as follows:

$$EMG_n = (EMG_w - EMG_{rest}) / (EMG_{RVE} - EMG_{rest}) \qquad \mathit{3.1}$$

where EMG_n is normalized EMG, EMG_W is the work-task EMG signal, EMG_{Rest} is the median of the middle 3 seconds of the EMG signal at rest (between 2 and 5 seconds of the 7-second rest period), and EMG_{RVE} is the median of the averaged middle 3 seconds of three EMG recordings during the RVE activity (between 2 and 5 seconds of the 7-second RVE activity period).

This method of normalizing the EMG signal further enhances the signal-to-noise ratio of each muscle recording, since subtracting the rest activity from both the work and RVE signals serves to reduce some of the effects of “noise” interference that may have existed in the laboratory at the time of the data collection period. Furthermore, normalization to the RVE, as opposed to the maximum voluntary electrical activity (MVE) acquired during the performance of maximal static contractions, is thought to be better suited to musicians, since most are unaccustomed to maximum isometric contractions. The motoneurone drive to the active muscle may therefore be more variable in an MVE contraction compared to an RVE contraction.

EMG Exposure Variation Analysis (EEVA)

The EMG signal recorded from each muscle was analyzed using methods similar to the exposure variation analysis (EVA) technique developed by Mathiassen and Winkel (1991). The root-mean-square (RMS) processed and normalized EMG signal was compared to a linear scale (beginning at 0 to 50% of RVE) of amplitude, and the period of time (logarithmic, base 2, beginning at 0 to 0.3 seconds) spent at each amplitude level is expressed in a 3 X 3 array. The array comprises 3 linear levels of EMG amplitude, namely <50%, 50% – 100%, and >100% of RVE, and 3 logarithmic (base 2) levels of time period, namely 0 – 0.3s, 0.3 – 1s, and >1s. These are the same as those used by Bao et al (1997), Mathiassen and Winkel (1996), and Hägg et al (1997).

The contents of each “bin” or cell in the array represent the percentage of total “work” time spent at each amplitude level and for each time period. The sum of all the bins is 100% of the total work (performance) time and therefore the cells in the array are considered proportions of the whole work task duration. EVA arrays similar to those used by Mathiassen and Winkel (1991), Anton (2002 a and b), Bao et al (1996), and Hägg et al (1997) were created from normalized data using the Statistical Analysis

System (SAS) statistical software program (SAS Institute, Cary, NC, USA). Please refer to Appendix E for the code used to create these EVA arrays.

Three-Dimensional Kinematic Data Collection

The, “Flock-of-Birds”, system (Ascension Technology Corporation, Burlington, VT, USA) was used with the MotionMonitor kinematic system (Innovative Sports Training, Chicago, IL, USA) to assess the relative motion of the components of the right shoulder using three-dimensional (3D) kinematics. Sensors were affixed to the trunk (*manubrium sterni*) and scapula (superior aspect of the postero-lateral acromion) using double-sided toupee tape, and to the humerus (attached to a molded polypropylene cuff of matching size to the participant’s arm, which was attached to the distal third of the upper arm with padded hook and loop straps (Velcro Industries BV, Manchester, NH, USA) and secured using Cramer Pre-Wrap (Cramer Products, Inc., Gardner, KS, USA). Local (anatomical) coordinate systems (LCS) were mathematically created and embedded into each segment by digitizing the positions of palpable bony landmarks in each of the segments (trunk, scapula and humerus) using matrix mathematics techniques (Craig, 1989).

These methods are similar to those used by Ludewig and Cook (2000) and Karduna et al (2001).

Local coordinate systems were set up for the trunk, scapula and humerus as follows:

Trunk (thorax)

The local or anatomical reference frame (LCS) is described in terms of, or relative to, the source of electromagnetic radiation (transmitter) or the Global Coordinate System

(GCS). The thoracic sensor was placed on the manubrium sterni at its flattest location and secured in place with doubles sided tape and a fabricated nest of layered tape.

Four points on the thorax (sternal notch (SN), xyphoid process (XP), C7 spinous process (C7) and T8 spinous process (T8)) were digitized. The positive Z-axis, represented by the k_T unit vector and corresponding to the vertical longitudinal axis of the trunk was estimated by first defining the Z_t axis (by determining the k_t unit vector which is determined by approximating the long axis of the trunk (with Z_t positive pointing upwards) as follows:

$$k_t = [(r_{SN/O} - r_{C7/O})/2 - (r_{XP/O} - r_{T8/O})/2] / [|(r_{SN/O} - r_{C7/O})/2 - (r_{XP/O} - r_{T8/O})/2|] \qquad 3.2$$

where *O* is the origin of the sternal sensor.

In this notation, r refers to the x, y, z coordinates of the point in the local coordinate system. Axes are then placed into a 4 x 4 matrix as represented below. The column vectors are the vectors which denote the local system axes in relation to the global (transmitter) system. The fourth column (X, Y and Z) denotes the translation of the local system in relation to the global system along the X, Y and Z axes respectively. The fourth row vector (0, 0, 0, 1) is added to complete a 4X4 matrix (as opposed to 3X4) which is easier to manipulate mathematically.

$$\left[\begin{array}{ccc|c} Xi & Xj & Xk & X \\ Yi & Yj & Yk & Y \\ Zi & Zj & Zk & Z \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

The 4X4 matrix used to represent the rotation and translation of a local sensor (which is affixed to the bony segment, i.e. scapula) or local anatomical coordinate system in relation to the global origin (the electromagnetic transmitter) or another local anatomical coordinate system.

Next, the X_t axis was defined with its positive direction pointing laterally. It is perpendicular to the plane defined by k_t and its cross product with $r_{C7/SN}$ is determined as follows:

$$i_t = k_t \text{ X } (r_{C7/SN}/|r_{C7/SN}|) \tag{3.3}$$

Lastly, the j_t unit vector corresponding to the positive Y_t direction and perpendicular to the k_t and i_t is determined as follows:

$$j_t = i_t \text{ X } j_t. \tag{3.4}$$

Scapula

Three points on the scapula were digitized (postero-lateral acromion (PLA)) root of the spine of the scapula (RS), and the inferior angle of the scapula (IA)). The scapula local co-ordinate system (LCS$_s$) was created as follows:

X_s: The i_s unit vector corresponding to the x_s coordinate direction is defined by

$$i_s= [(r_{AC/O} - r_{RS/O}) /|(r_{AC/O} - r_{RS/O})|] \tag{3.5}$$

where $_{AC/O}$ is the relative position of the PLA in relation to the scapula sensor and $_{RS/O}$ is the relative position of the root of the scapula in relation to the scapula sensor. The scapula sensor was placed on the superior plateau of the posterior acromion which remains largely unencumbered by soft tissues during shoulder abduction, and secured using double-sided tape.

Y_s: the j_s unit vector corresponding to the positive y_s axis coordinate direction and perpendicular to the scapula plane is defined as follows:

$$j_s= i_s \text{ X } [(r_{IA/O}-r_{AC/O})/|(r_{IA/O}-r_{AC/O})|] \tag{3.6}$$

Z_s: k_s is the unit vector corresponding to the positive z_z coordinate direction and is defined as follows:

$$k_s = i_s \text{ X } j_s \tag{3.7}$$

Humerus

The medial (ME) and lateral (LE) epicondyles were digitized. The glenohumeral joint (GHJ) center was mathematically determined by the MotionMonitor system using methods described by Meskers et al (1998). The humeral local coordinate system (LCS_h) was determined by defining the Z_h axis first which is positive in the vertical direction and which approximates the vertical axis of the humerus. The humeral sensor was firmly secured to a thermo-plastic polypropylene cuff which was in turn secured to the distal third of the humerus using tape and foam underwrap (Cramer Pre-Wrap, Cramer Products, Inc., Gardner, KS, USA).

$$k_h = [(r_{ME/O} - r_{LE/O})/2 - GHJ]/|[(r_{ME/O} - r_{LE/O})/2 - GHJ]| \qquad 3.8$$

where O is the origin of the humeral cuff sensor to which the humeral sensor was affixed and GHJ is the center of the glenohumeral joint.

Next the Y_h axis was defined with its positive direction pointing anteriorly in relation to a line joining the medial and lateral epicondyles of the humerus as follows:

$$j_h = k_h \times [(r_{LE/O} - r_{ME/O})/|(r_{LE/O} - r_{ME/O})|] \qquad 3.9$$

Lastly, the X_h axis was defined positive in the lateral direction to the right as follows:

$$i_h = j_h \times k_h \qquad 3.10$$

Each bony segment (trunk, scapula and humerus) is assumed to be a rigid structure, despite the fact that in the trunk this is not the case. Motion contributed by the sterno-clavicular and acromioclavicular joints was ignored and motion of the scapula was described in reference to the trunk as described above.

In the zero degree angular position, the vertical axis is termed the “Z-axis” (emanating orthogonally from the transverse plane and positive in the upward direction), the horizontal lateral axis is termed the “X-axis” (emanating orthogonally from the sagittal plane and positive towards the right), and the horizontal antero-posterior axis is termed the “Y-axis” (emanating orthogonally from the coronal plane and is positive in the forward direction).

The relative motion of these 3 segments was captured at a sampling rate of 100 Hz and expressed using the standard Euler/Cardan angle rotation sequences similarly to those used by Ludewig and Cook (2000), Karduna et al (2001), and van der Helm (2001), namely

1. Z Y’ X” (external/internal rotation followed by upward/downward rotation followed by anterior/posterior tipping) for the scapula motion about the trunk, and
2. Y X’ Z” (elevation followed by flexion/extension or more correctly horizontal flexion and extension in the elevated position, followed by internal/external rotation) for humeral motion in relation to the scapula.
3. ZY’Z” (arm plane of elevation, followed by arm elevation, followed by internal/external rotation) of the humerus relative to the trunk.

The choice of these rotation sequences ensured that gimbal lock singularity was avoided in expressing the relative motion of these segments. These rotations facilitate description of the motion in a manner that makes clinical sense, and with less error than projection angle or joint coordinate system methods.

These methods employ surface-mounted sensors which are prone to motion artifact that digital filtering cannot eliminate. Ludewig et al (2002) determined that such error (root mean square (RMS) differences) could be kept as low as 3.1 to 3.8 degrees for humeral flexion, 1.3 to 3.5 degrees for scapular plane abduction, and 1.3 to 7.5 degrees for humeral internal and external rotation when surface-mounted sensor data was compared with motion data from sensors mounted to bone pins. RMS errors for translation along these axes were even lower (0.1 to 2.1 mm) for the same motions. Karduna et al (2001) validated surface-mounted motion sensor measurement to motion measured with sensors attached to intracortical bone pins. RMS errors for rotation about the three rotational axes were 6.6^o for scapula tilting, 9.4^o for internal/external rotation, and 6.3^o for upward rotation across full motion of the arm. There was improved agreement between the bone pin-mounted sensors and the surface-mounted sensors below 120^o of humeral elevation.

Therefore, Cardan and Euler angle methodology was chosen for this study as a suitable motion analysis method to express the 3-D motion of scapulothoracic and glenohumeral motion.

The motion data were sampled in synchrony with the EMG data and an interpolation technique was used by the MotionMonitor™ system (Innovative Sports Training, Chicago, IL, USA) to “fill” data points since the EMG data was sampled at 1000 Hz. The kinematic data were then digitally re-sampled at 100 Hz (their original sampling frequency) to facilitate EVA processing in a similar fashion to the EMG data.

Hägg et al (1997) used EVA to assess the exposure of automobile assembly line workers to awkward wrist postures using an electronic goniometer. Jansen (1999) has used the EVA technique to assess the relative risk of spinal flexion (sagittal plane flexion) activities in nurses and train attendant occupations from electronic goniometer data-logger data. Anton (2002 a and b) used the EVA technique to assess the exposure of operating engineers and construction workers to forearm muscle activation in relation to carpal tunnel syndrome. No previous researchers have used an exposure variation analysis to assess occupational hazards using three-dimensional kinematic data.

Kinematic Exposure Variation Analysis (KEVA)

The kinematic data from each segment were analyzed using 3X3 exposure variation analysis (EVA) arrays which were slightly modified compared to those used by Hägg et al (1997). The kinematic data (motion of one segment in relation to that of another) were divided into three amplitude levels by dividing the range of data between the 5th and 95th percentile in the uninjured group into equal thirds for each dependent variable. This range was chosen to be robust against the effect of outlying observations. End amplitude levels encompass values greater-than and less-than the midrange in each case. All kinematic data from both groups were then compared to this “trimmed data range” individually for each dependent variable. The original methodology of analyzing kinematic data was abandoned since tertiles of the data were too narrow and resulted in some participant's data not ever crossing the amplitude margins, and those whose kinematic signals did cross misrepresented the frequency of kinematic performance. This may have been the result of different musicians commencing at varying static postures due to stylistic preference, or violin pedagogy. Normalizing musicians to a starting posture may have resulted in eliminating possible reasons for their injury status by virtue of their static resting posture. Dividing the total range of kinematic signal in the uninjured group was also investigated and this was found to be unsatisfactory as the level margins were highly sensitive to outliers, since the maximum kinematic excursion and minimum kinematic excursions in two participants determined the bin margins.

Time periods were divided into logarithmic (base 2) row vectors similarly to the EEVA analysis described above. The array therefore comprises three linearly spaced levels of kinematic excursion and three logarithmic levels of time period, namely <1s, 1s – 3s, >3s. The contents of each bin in the array represent the percentage of total "work" time spent at each kinematic variable level and for each time period. The sum of all the bins is therefore 100% of the total work time. EVA arrays similar to those used by Mathiassen and Winkel (1991), Anton (2002 a and b), Bao et al (1996), and Hägg et al (1997), but with the above-mentioned modifications, were created from kinematic data using the Statistical Analysis System (SAS) statistical software program (SAS Institute, Cary, NC, USA). Please refer to Appendix E for the code used to create these EVA arrays.

Work Task Data Collection

Following Rest and RVE data collection, the participant was instructed to “warm up” with their instrument as if preparing for a regular practice session. After suitable rest (the participant indicated when he/she was ready for performance) following the warm-up, each participant played, in randomized order, four fast and four slow 30-second trials of the *Frisch Etude* (Frisch, M, 2005) which was written especially for this study (Appendix G). The etude was played once through at 60 beats per minute (bpm) and is classified as, “slow repertoire” for this study, and eight times through at 160 bpm, which is classified as, “fast repertoire”, which also lasted 30-seconds. Musicians were provided with two separate musical scores with the slow performance score comprising only one run of the repertoire marked for 60 bpm pace, and the fast repertoire comprising the same score marked for 8 repeats to be played at 160 bpm. The music used for this study was written in this way so as to evaluate the sensitivity to speed of the EVA data reduction technique, since fast and slow repertoire demand that the bow is on the strings in the same proportion of time, but at a different frequency.

Etudes are practice exercises that are used by string musicians to master various bowing and performance techniques. Although their performance is not quite the same as performing classical musical repertoire (Okner, 1997), they enable the listener to observe essential skills and techniques that the musician strives to master. The Frisch Etudes for this study were played 4 times at each speed (fast and slow) in order to facilitate assessment of the repeatability of the EVA technique with identical tasks (Hypothesis 1).

Participants were provided with the musical scores at least 2 weeks prior to the data collection session in order to allow them time to familiarize themselves with the music, the two different performance speeds, and the skill required to play the piece 8 times through at 160 bpm, which in some cases proved to be difficult for some participants. In addition, they were provided with a digital recording of the music in an electronic format, either on compact disc (CD), or sent to them using electronic mail, in order to eliminate confusion about the speed of performance. Use of this type of repertoire in pilot research (Reynolds and Ludewig, 2002) indicated that musicians are not always consistent in their interpretation of repertoire when sight-reading. In previous research it was also found that some participants were more familiar with the repertoire than others (Reynolds and Ludewig, 2002) and that provision of the musical score and recording early on serves to ensure that these effects are minimized. This was not the case in this study since the music was specifically written for the study. The pace of performance was controlled using a digital metronome (*Qwik Time*, Evets Corporation, Laguna Hills, CA, USA). The beat was audibly and visually perceived (the metronome has a light emitting diode that the musician could see during performance to keep time).

Statistical Methods

Summary statistics were generated on basic demographic data, medical history, musical performance history, and physical examination data to assess for differences between the two groups. Student's t-tests were used to assess these differences and a significance level of 0.05 was used to discern differences between the two groups.

Continuous electromyographic (EMG) and kinematic data were reduced using previously described exposure variation analysis (EVA) techniques. As noted before, these are a modification of the methods first proposed by Mathiassen and Winkel (1991). Since this study covers a relatively short time period, modifications were necessary since the EVA technique was designed to be used to assess the exposure of an individual to various continuous variable data, such as EMG, kinematics, heart rate, etc. over a longer period of time.

Exposure Variation Analysis (EVA)

Time duration and signal scales are each divided into categories using pre-defined cutoffs. For example, time may be divided into categories of short, medium, and long duration while signal may be divided into weak, medium, and strong signals. These divisions create m X n categories, called cells, summarized in the EVA, where m is the number of time duration categories and n is the number of signal categories. Based on these definitions, the continuous signal over the course of a single trial is then divided into segments based on duration and signal strength, e.g. a medium strength signal held for a long duration. Each segment, and in turn, each measurement may then be labeled by the number of the EVA cell to which it belongs. The EVA is defined as the proportion of individual measurements that fall into each EVA class, representing the proportion of time in the overall trial spent in segments of each combination of time duration and signal strength categories. The results are often summarized as a two-dimensional table, ordered on each axis by time duration and signal strength.

By labeling the individual measurement by the EVA cell label to which it contributes, we obtain a data set consisting of 3000 observations of a nominal outcome (EVA cell) per trial, with 8 trials per subject. Each EVA array can therefore be thought of as a sample of 3,000 correlated draws from a multinomial distribution. with error variance for injury (v_i) and speed (u_{ij}), as well as overall error (ε_{ijk}^{c}).

The data are further organized in a hierarchical structure, referred to as *clustered* or *nested* data. That is, each individual observation (Level 1) belongs to a single trial (Level 2) and each trial is performed by a single research participant (Level 3). Because of this nesting, individual multinomial response data do not represent statistically independent observations, but may have correlation due to both within-trial (Level 2) and within-subject (Level 3) effects.

The appropriate method for analysis of such data is mixed-effects multilevel logistic regression for nominal (unordered) discrete response data as described by Goldstein (1999). More specifically, random effects models are used to incorporate random effects for trial and subject. This allows the introduction of correlations within-subject and between-trial.

The general model is defined as follows (Hedeker and Gibbons (2006)): Let y_{ijk} denote the dependent variable (EVA cell) for person i ($1 \le i \le 50$), in trial j ($1 \le j \le 8$) at time k ($1 \le k \le 3000$). Let P^{c}_{ijk} be the probability that measurement k in trial j for person i is equal to c, conditional on the model parameters, where c is an EVA cell number. Letting $c=r$ be the reference cell for comparisons, we model the log risk ratios, or logits, as:

$$z_{ijk}^{c} = \log\left(\frac{P_{ijk}^{c}}{P_{ijk}^{r}}\right) = \left(X\beta^{c}\right)_{ijk} + v_i^{c} + u_{ij}^{c} + \varepsilon_{ijk}^{c} \tag{3.11}$$

where β consists of the fixed effects covariates, such as speed and injury, *X* is the design matrix for the fixed effects, v_i is the random intercept for injury in person *i*, u_j is the random intercept for trial *j* within person *i*, and $\square_{ijk}$ is the random error for the *k*th measurement in trial *j* for person *i.* Furthermore, we assume the random effects are identically and independently distributed as:

$$\{v_i^c\} \sim N(0, \sigma_v^2), \ \{u_{ij}^c\} \sim N(0, \sigma_u^2).$$

The exact distribution of the residual error terms ε_{ijk}^c is not closed form, and may depend on the expected value of the outcomes (Hedeker and Gibbons, 2006). We will denote this unknown variance by σ^2 .

Note that there are different estimates of the fixed and random effects for each contrast *c* versus the reference cell *r.* Note further that there are different random intercepts for trial for each person.

It follows that the correlation structure is modeled as follows:

$$\mathrm{var}(z_{ijk}) = \sigma_v^2 + \sigma_u^2 + \sigma^2, \tag{3.12}$$

$$\mathrm{cov}(z_{ijk}, z_{ijl}) = \sigma_v^2 + \sigma_u^2 \tag{3.13}$$

, for *k≠l* (i.e. from the same person and trial), and

$$\mathrm{cov}(z_{ijk}, z_{ipq}) = \sigma_v^2 \tag{3.14}$$

, for *j≠p* (i.e. from the same person but different trials).

Measurements from different persons are assumed to be independent.

Under this assumption, the original model probabilities may be recovered as:

$$P_{ijk}^{c} = \frac{\exp\left(z_{ijk}^{c}\right)}{1+\sum_{h \neq r} \exp\left(z_{ijk}^{h}\right)} \text{ for } c \neq r, \text{ and} \qquad 3.15$$

$$P_{ijk}^{r} = \frac{1}{1+\sum_{h \neq r} \exp\left(z_{ijk}^{h}\right)} \text{ for } c=r, \text{ the reference category.} \qquad 3.16$$

Models were fit by maximum likelihood estimation, using the *SuperMix* software program for nominal mixed-effects models (Scientific Software International, Inc., Lincolnwood IL, USA, http://www.ssicentral.com), developed by Hedeker (2003).

In this study, the covariates of primary interest include speed (fast and slow), and group (injured and non-injured) and their interaction. Other fixed covariates included age (continuous) and gender. While we are underpowered to conduct subgroup analyses for age and gender alone, these covariates are included in the models to adjust for differences between the injured and non-injured groups.

Final results include estimates of the parameters for the fixed effects for each comparison of a cell to the reference cell and estimates of the variances, σ_v^2 and σ_u^2, and of the random intercepts and their standard errors. Furthermore, for each cell comparison to the reference cell, odds ratios and their 95% confidence intervals for each fixed effect are reported, showing the contribution of the fixed effect to the relative risk of a measurement falling in cell *c* as compared to the reference cell *r*.

Logistic regression is typically used to establish the relationship between predictor variables and a dichotomous dependent variable. Despite the fact that logistic regression methods are more often used in epidemiological research to identify the presence or absence of disease (Kleinbaum et al, 1998), it is being used in this study to discern differences between two groups whose injury status is already known.

It is often desirable to report the components of variance as an Intraclass Correlation Coefficient (ICC). ICCs [1,1] were determined for kinematic and EMG data by fitting a one-way analysis of variance ANOVA), with EVA cell count as the dependent variable (1 for fast and one for slow), and subject ID with their respective 4 trials (4 trials for each speed) as the independent variable. The ICC outcome was therefore computed as follows:

$$ICC = (MSM - MSE) / (MSM + (k-1)*MSE) \qquad 3.17$$

Where:

1. MSM is the Model Mean Square, or the between-person sum of squares divided by model degrees of freedom (df), and is essentially the between-person variance
2. MSE is the Mean Square Error, or the within-person sum of squares divided by the remaining df, and is essentially an estimate of the error variance δ^2.
3. k is the number of trials .

ICCs were calculated for each cell in the EVA array for fast and slow repertoire, for each dependent variable (kinematic and EMG).

The reliability of the EVA data reduction method was further verified by calculating the Standard Error of the Measurement (SEM) for each cell of the EVA for each speed (fast and slow) for all kinematic and EMG variables. Since the EVA comprises percentages of time spent at a particular amplitude level for duration of time, SEM values were expressed in percentages. The SEM was calculated as follows:

$$SEM = \sqrt{MSE} \qquad 3.18$$

Unless otherwise indicated, cell 5, representing moderate signal strength for moderate duration, was used as the reference category. In certain models, cells with very low frequency were combined in order to obtain reliable estimates of the parameters. These will be noted in the discussion of results.

Several different variable sets were chosen as fixed effects in order to address study hypotheses. Fixed effects for speed were assessed first, after which fixed effects for injury, adjusting for speed, were assessed. A significance level of 0.05 was used for all comparisons.

Adoption of this model satisfies the assumption that data is correlated without eliminating data as has been performed by Jensen et al (1999) and Anton (2002 a and b). Other researchers (Mathiassen Winkel, 1996; Bao et al, 1997; Hägg et al, 1997) ignored the fact that data within the EVA arrays are correlated and, therefore, used models that did not account for this relationship.

Three categories of analysis were performed to address specific study hypotheses:

1. Speed only, to evaluate differences in EVA due to change in speed of performance.
2. Speed, Injury, and Interaction between Speed and Injury.
3. Speed, Injury, Age, Gender, and Speed*Injury Interaction.

The cell assignment in all EVA arrays is as follows:

3	6	9	High *	Amplitude Axis
2	**5**	8	Medium	
1	4	7	Low *	
Low	Medium	High		

Time Period Axis

* High and Low amplitudes are reversed for Scapula Tilting and Glenohumeral Abduction, where Cells 1, 4, 7 are High Amplitude, and Cells 3, 6, and 9 are Low Amplitude.

All EVA cells are referenced to cell 5 in the analyses. Odds ratios greater or less than 1 can therefore be thought of as vectors of change in a particular direction in the EVA. For example, if the fixed effect for speed in the comparison of cell 1 to cell 5 shows an odds ratio greater than 1, this indicates that there were greater odds that at the high speed, the signal (voltage on EMG and range in kinematic analysis) would fall in Cell 1 compared to Cell 5, representing a shift towards shorter duration, which can imply higher frequency, and lower amplitude in all variables except Scapula Tilting and Glenohumeral

Abduction (where the orientation is reversed). It is possible that if cell 5 were to change and only one other cell in the array was to change (i.e. cell 5's change was to be "absorbed" by another cell) then it would still be possible to see changes in odds ratios other than the two cells in question, and this may have no clinical relevance because no actual change in the cell of interest occurred.

In the assessment of injury effects for kinematic and EMG variables, a decision tree as to the significance of the effect (magnitude of the odds ratio) and its clinical relevance is determined in the following manner:

1. Assess the significance of the odds ratio by observing the p-value and the confidence interval.

2. Assess the magnitude of the odds ratio: a value less than 1 indicates a reduced likelihood of the measurand being in the cell concerned compared to the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood that the measurand being in the cell concerned compared to the reference cell.

3. Assess the change in the magnitude, if any, in the odds ratio in cell 5. If the odds ratio does not change in cell 5, this suggests that odds ratios greater than or less than 1 may be clinically relevant in the other cells, and their significance will depend on 1 above. If the odds ratio decreases in cell 5 this would indicate a dampening effect on cells whose odds ratios showed an increase by about the same proportion. If the odds ratio in cell 5 increases, this would indicate a

dampening effect on cells whose odds ratios showed a decrease by about the same proportion.

4. Assess the changes, if any, in the EVA graphs and relate these to the statistical analysis.

In terms of the overall analysis of Speed, Injury and the interaction between Speed and Injury, information about the EVA changes seen in the graphs can be explained by the odds ratios as follows:

Change	**Odds Ratio**
Uninjured Slow to Injured Slow	Injury
Uninjured Slow to Uninjured Fast	Speed
Injured Slow to Injured Fast	Speed X Interaction
Uninjured Fast to Injured Fast	Injury X Interaction

Statistical Power

To avoid Type II error in all the hypotheses mentioned above, statistical power of 80% was sought to detect a 10% difference between each cell within a particular array. From the pilot data (Reynolds and Ludewig, 2002), the highest standard deviation observed was 20% (0.2). Therefore, for a Z-ratio of 1.96 and a standard deviation of 0.2, the formula to determine an adequate sample size using the standard deviation (0.2) of the difference between two proportions is as follows:

$$\left[\frac{0.2\sqrt{2}}{\sqrt{n}}\right]\times 1.96 < 0.1 \qquad 3.19$$

indicating the need to recruit 25 participants per group, with a total sample size of 50. A sample of 25 injured (violinists with subacromial impingement syndrome) and 25 uninjured musicians were therefore sought to participate in this study.

Additional Analyses

1. For the purposes of comparison with other studies that have investigated subacromial impingement (Lukasiewicz et al, 1999, Ludewig and Cook, 2000, Graichen et al, 2001, McClure et al, 2006), separate analyses were performed on the kinematic and EMG data for Arm Elevation between 50 degrees and 65 degrees, a posture that is most likely to be associated with impingement in the injured group. Correlation co-efficients were determined for all dependent variables, both kinematic and EMG, as well as potential covariates of age, gender, and Arm Plane Elevation. Based on these correlation analyses, as no covariate had a correlation with any dependent variable higher than 0.65, no analysis of covariance was deemed necessary. A two-way analysis of variance was used to determine main effects for speed (fast and slow) and injury (injured and uninjured), as well as for interactions between these variables.

2. Resting scapula posture was recorded at rest for injured and uninjured participants. Resting scapula postures were compared using Student’s t-tests.

3. Resting scapula posture was observed visually prior to commencing with data collection and recorded as being either, “normal” or, “abnormal” in terms of 3

rotations, namely upward/downward rotation, anterior/posterior tilting (tipping) and internal/external rotation. Upward/downward rotation was deemed to be abnormal if the medial border of the scapula was downwardly rotated past the vertical. Anterior/posterior tilting was deemed to be abnormal if the inferior angle of the scapula was prominent relative to the thorax. Internal/external rotation was deemed to be greater than normal if the medial border of the scapula was prominent relative to the thorax. These rotations were measured in the seated resting position using the “Flock-of-Birds” motion analysis system, and correlations between observed determinations were compared to 3-D measurement of these rotations. For the purposes of this study, the normal values for scapula orientation in the resting position were: Upward rotation $\leq -2^{o}$ (i.e. a position of 2 degrees of upward rotation), anterior tilting $\geq -11^{o}$, and medial rotation $\leq 32^{o}$ (Ludewig and Cook, 2000, Culham and Peat, 1993). Determinations of observed scapula orientation were compared to those determined kinematically using the Flock-of-Birds system and Fisher’s Exact Test, assessing the agreement between the two assessments of scapula orientation. Fisher’s Exact Test evaluates the agreement in a 2X2 contingency table and is more appropriate than a Chi-Squared analysis when column totals are expected to be low.

4. The reliability of the measurement of various scapula, glenohumeral, arm, and EMG variables was assessed by calculating intraclass correlation co-efficients (ICC) from raw data at three different time periods, 5 seconds, 15 seconds and 25 seconds over 50 ms time windows for each speed condition.

Limitations of the Methods

1. The repertoire used in this study was written specifically for this study and may not be truly representative of repertoire that is commonly played by professional or amateur musicians. The musical score required the violinist to play on all 4 strings with “up-bow” and “down-bow” motions, thereby affording analysis of right shoulder motion in all positions over the course of the 30 second performance. Furthermore, the fast repertoires was written such that the duration of play was the same, but the exposure was proportional to that of the slow piece, since the fast repertoire was the same musical notes, played 8 times faster.

2. The three bony segments used for kinematic analysis (trunk, scapula and humerus) were regarded as being rigid bony structures, despite the fact that the trunk comprises multiple moving segments. Sites for sensor placement were chosen to minimize the effects of these motion artifacts, and significant care was taken to anchor these to minimize unwanted motion.

3. Motion at the AC and SC joints was ignored and the motion of the scapula was analyzed relative to the trunk.

4. Movement of the motion sensors (motion artifact) on the skin was inevitable and could only be reduced by inserting bone pins into the bony segments under analysis. This would not have been a viable method of analysis in this group of musicians.

5. EMG measurement is assumed to represent the electrical activity in the whole muscle, despite the limitations of this imposed by surface measurement at one location only. The influence of extraneous “noise”, as well as motion of soft tissue beneath the electrodes was inevitable, and significant care was taken to reduce these effects.

6. SIS is believed to be impacted by several factors, including muscular imbalance between serratus anterior and lower trapezius, upper trapezius, levator scapulae and rhomboid, to name only a few. The muscles chosen have been shown to play a significant role in identifying abnormal muscular balance in SIS.

7. EVA is a relatively new method of exposure analysis, and statistical analysis of this method has been problematic. The viability of this method still needs to be conclusively established.

8. Kinematic and EMG bin margins for time period and amplitude were chosen in relation to the distribution of the data and, if chosen differently, may have revealed different results.

9. Although this study modeled different covariances for observations drawn from the same trial versus different trials within the same person, the covariance structure does not vary much over time with trial. While the covariance structure based on random intercepts is widely used in many applications, a more sophisticated covariance structure may provide a better model fit. However, the lack of commercially available software for fitting such models limits the pursuit of a more detailed covariance structure.

Figure 3.1. Full-size violin showing total length and string length (bridge to scroll).

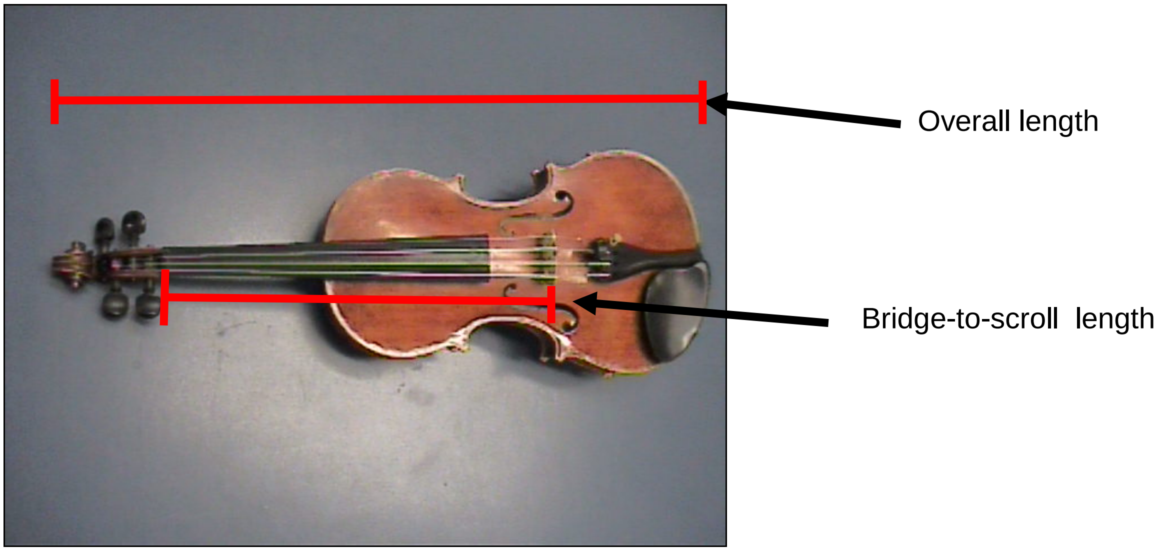


Figure 3.2. Measuring the weight of the violin using the *Pinch*Track™ pinch dynamometer (JTech Medical Industries)

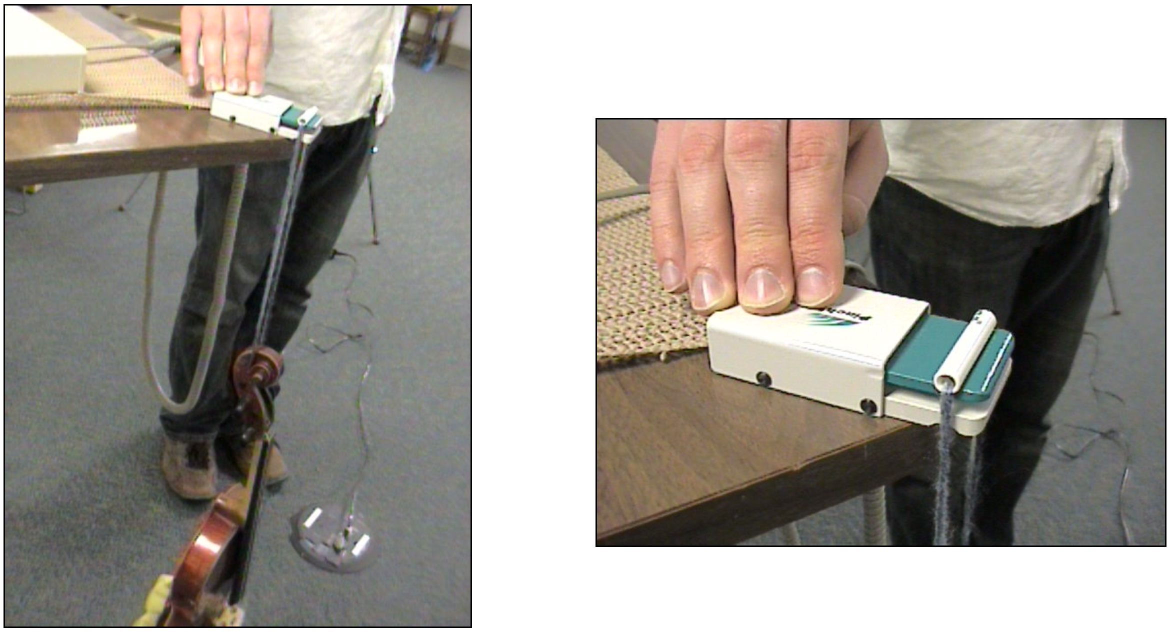


Figure 3.3. Proximal end of a full-size violin showing “Active Neck Height” and shoulder rest.

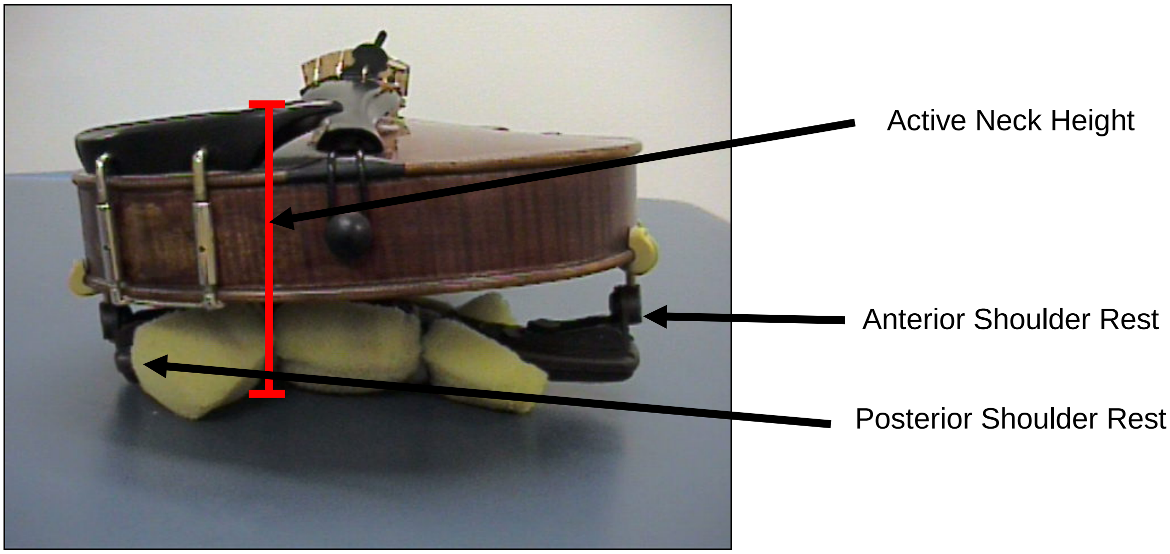


Figure 3.4. Side of a full-size violin showing the bridge height.

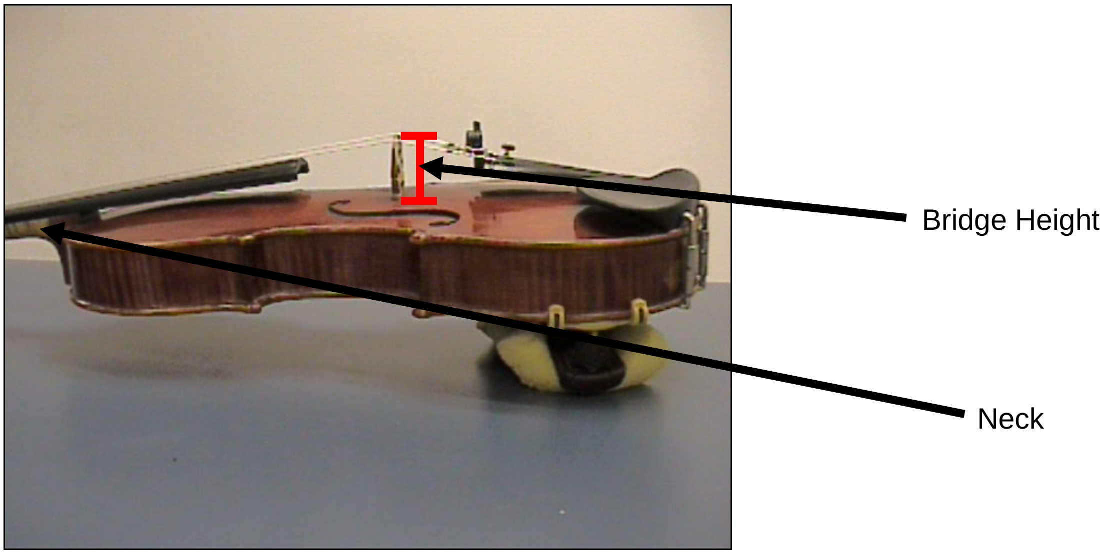


Figure 3.5. Full-size violin bow showing the length of the, “hairs” of the bow.

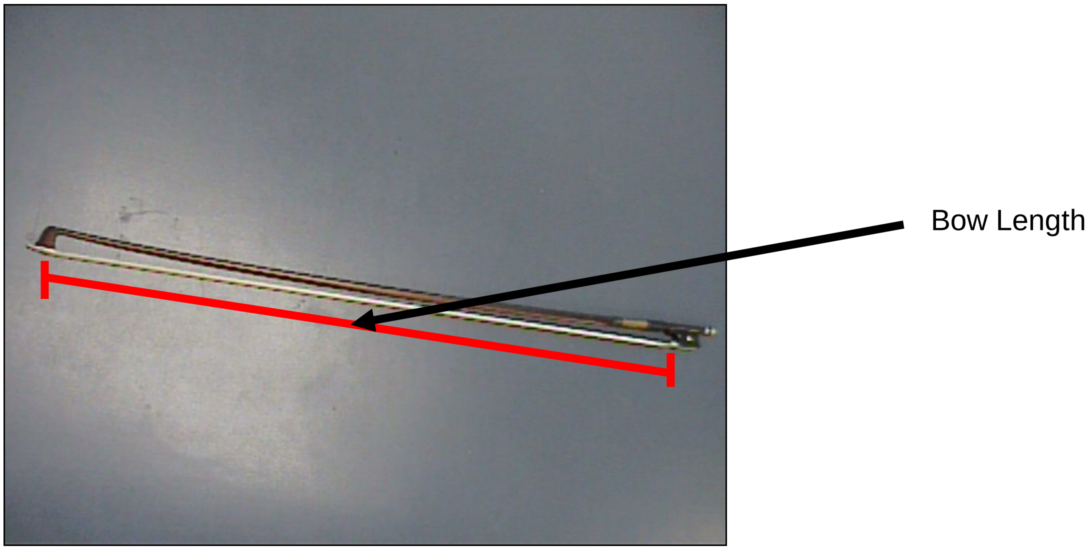


Figure 3.6. EMG electrode and MotionMonitor™ kinematic sensor placement.

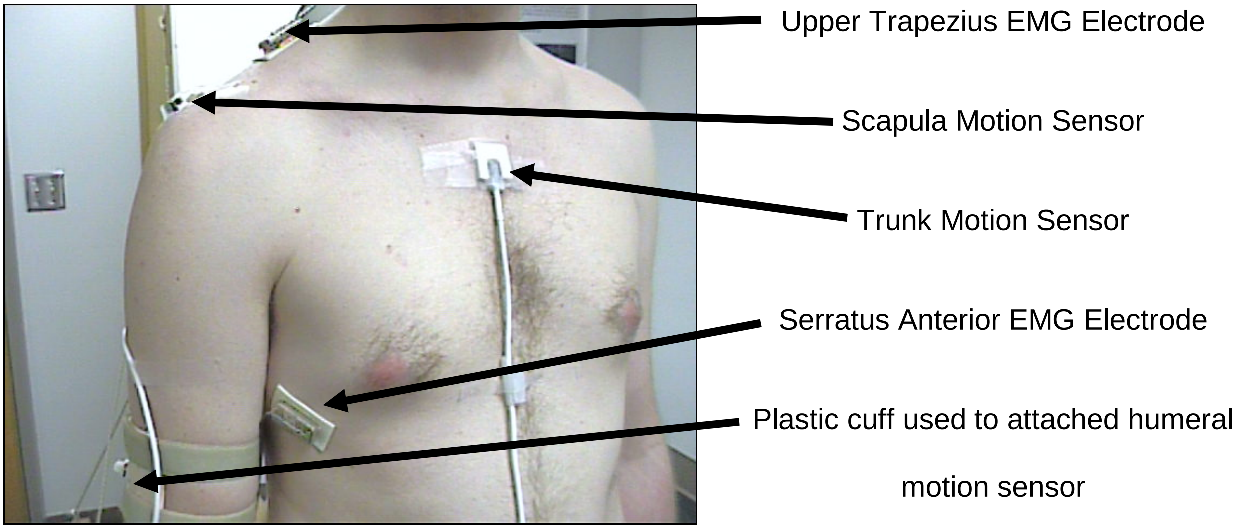


Figure 3.7. EMG electrode and MotionMonitor™ kinematic sensor placement.

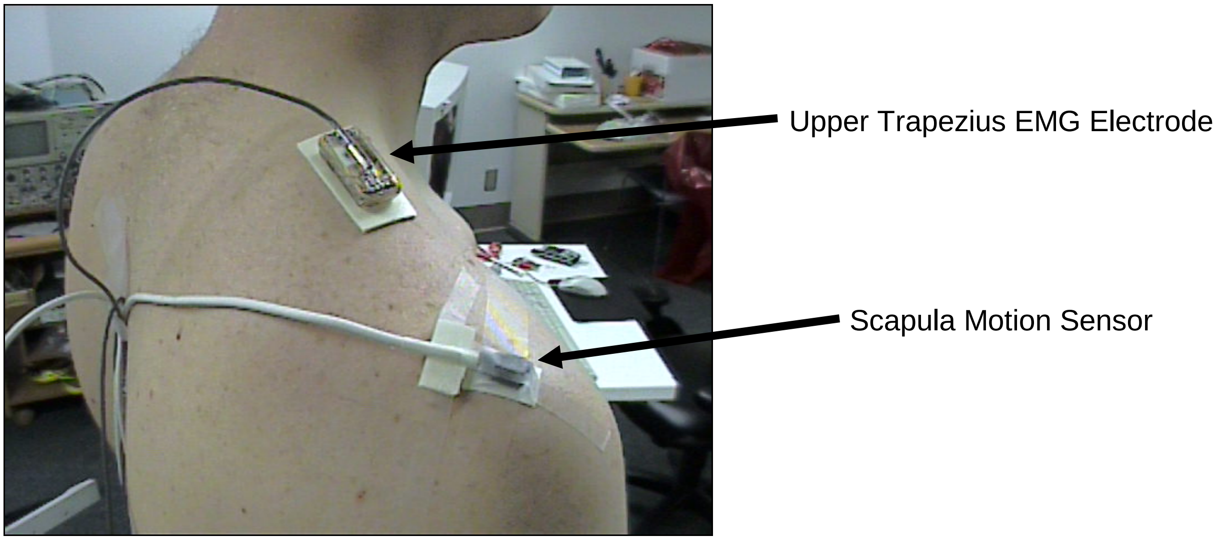


Figure 3.8. Right Upper Trapezius Relative Voluntary Electrical (RVE) activity EMG Measurement.

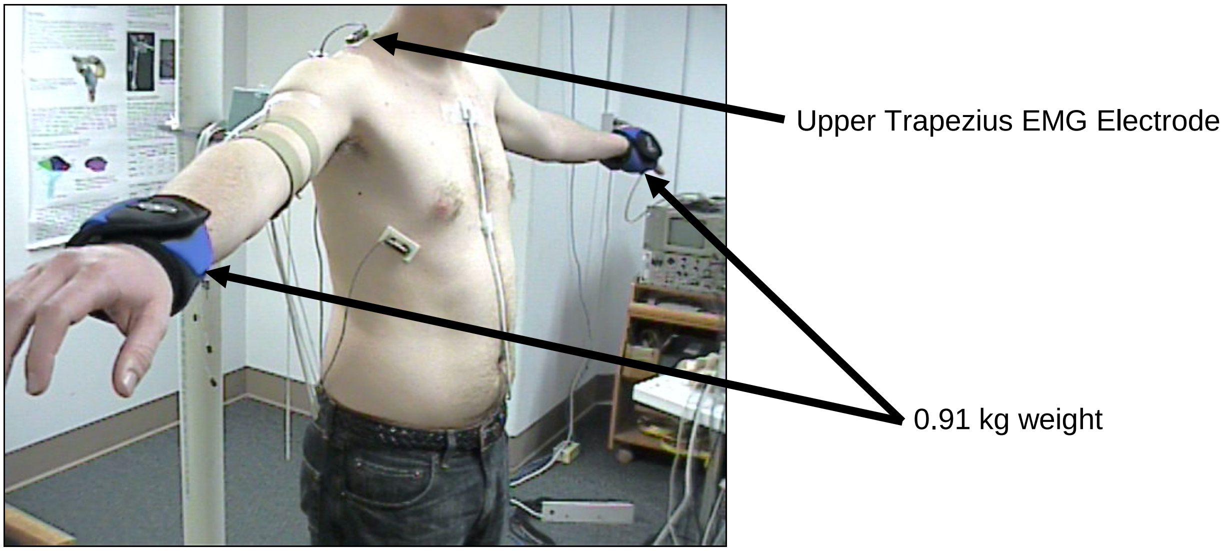
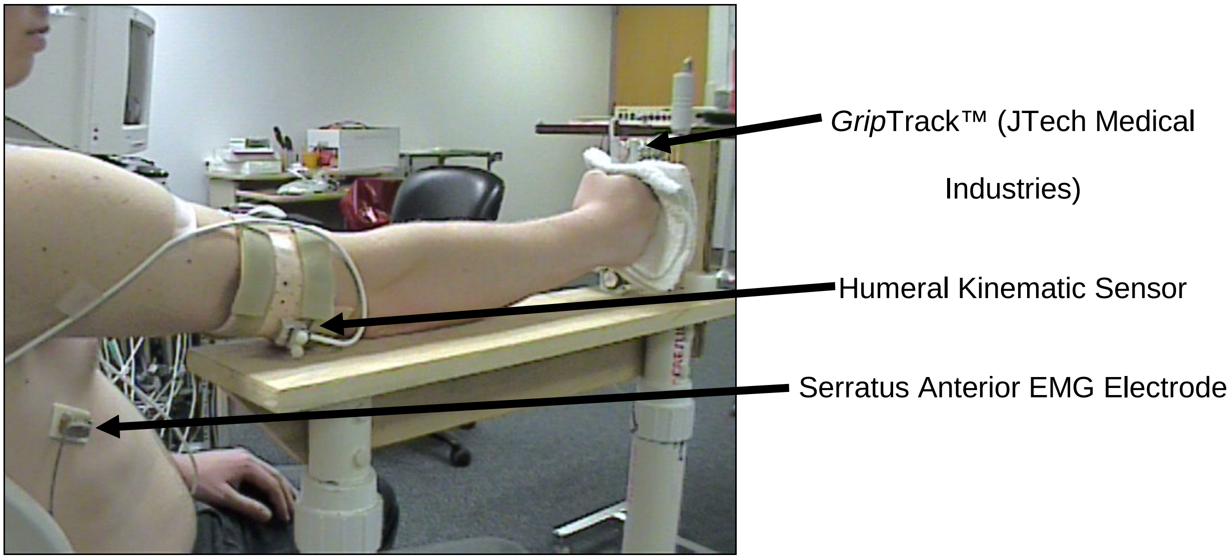


Figure 3.9. Right Serratus Anterior Relative Voluntary Electrical (RVE) activity EMG Measurement.

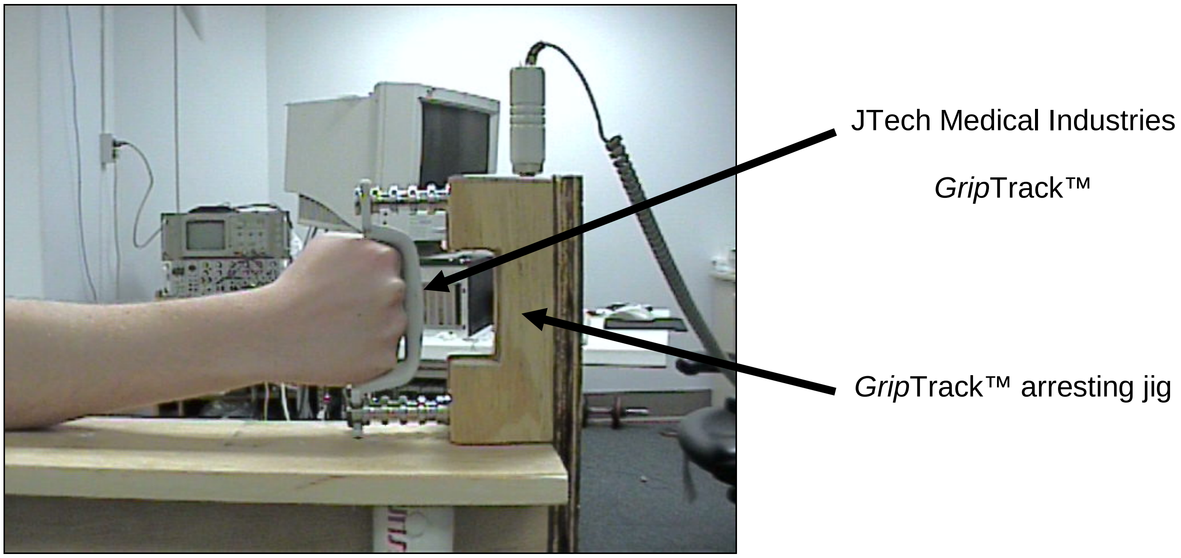


*Grip*Track™ (JTech Medical Industries)

Humeral Kinematic Sensor

Serratus Anterior EMG Electrode

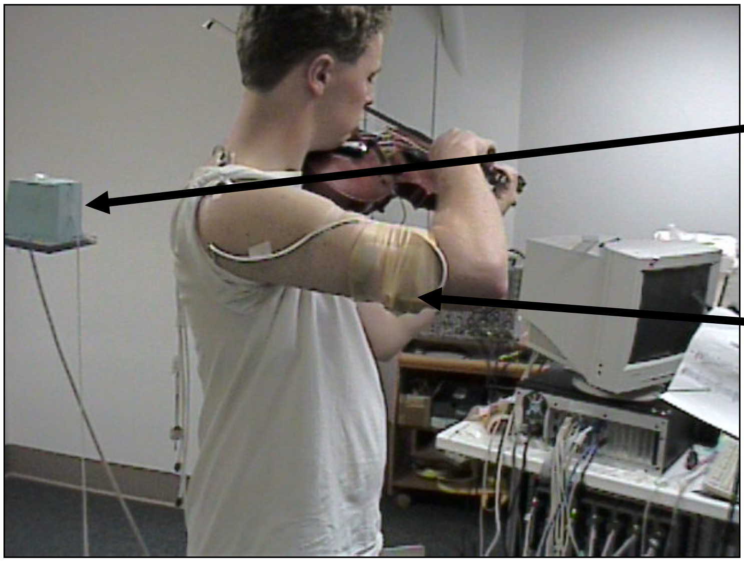
Figure 3.10. Right Serratus Anterior Relative Voluntary Electrical (RVE) activity EMG Measurement.



JTech Medical Industries *Grip*Track™

*Grip*Track™ arresting jig

Figure 3.11. Participant at the end of the “up-bow” bow stroke on the “G-String”.



Electromagnetic Transmitter

Humeral kinematic sensor attached

to plastic molded cuff

Figure 3.12. Participant playing at the end of the “down-bow” bow strokke on the “E-String”.

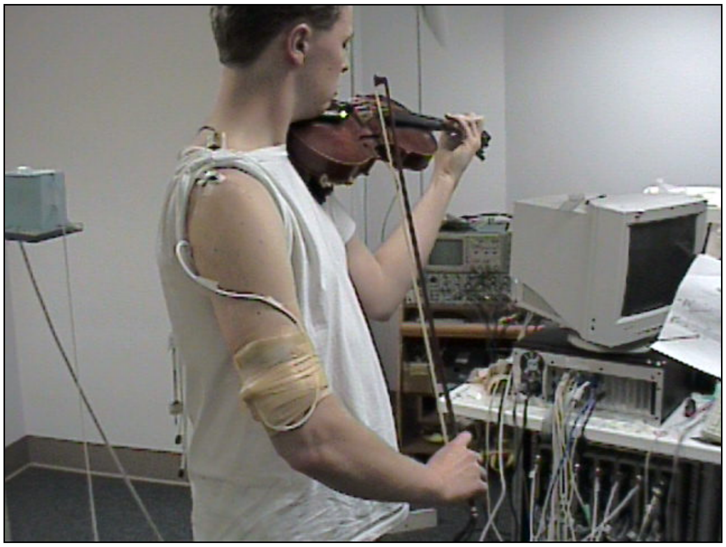


Figure 3.13. Full-size violin from the musician's perspective showing the 4 strings from right to left, E, A, D and G.

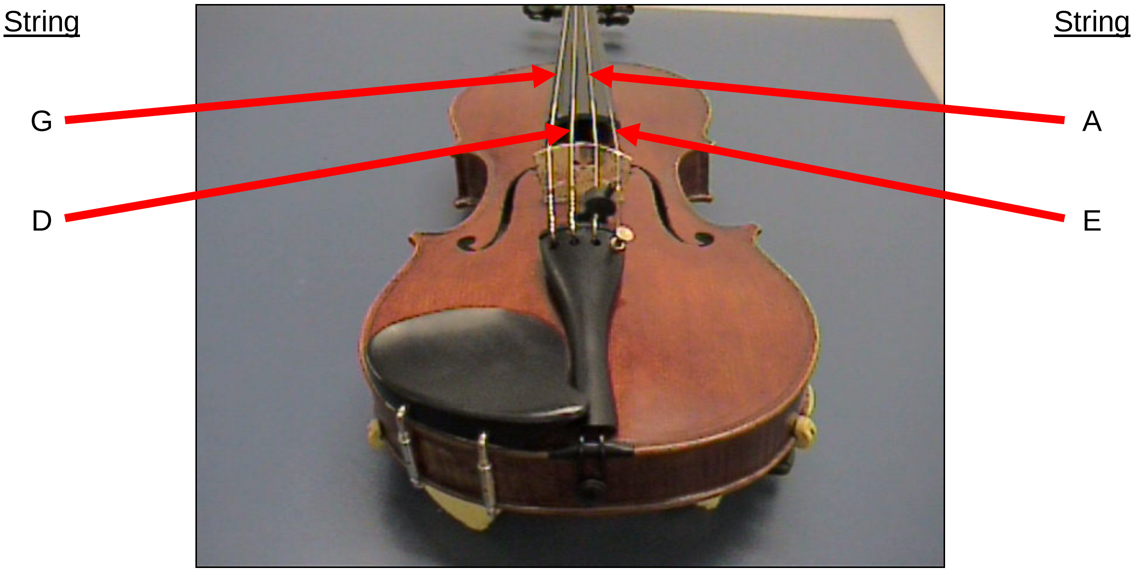


Figure 3.14. Thorax viewed from the right side showing axis orientation.

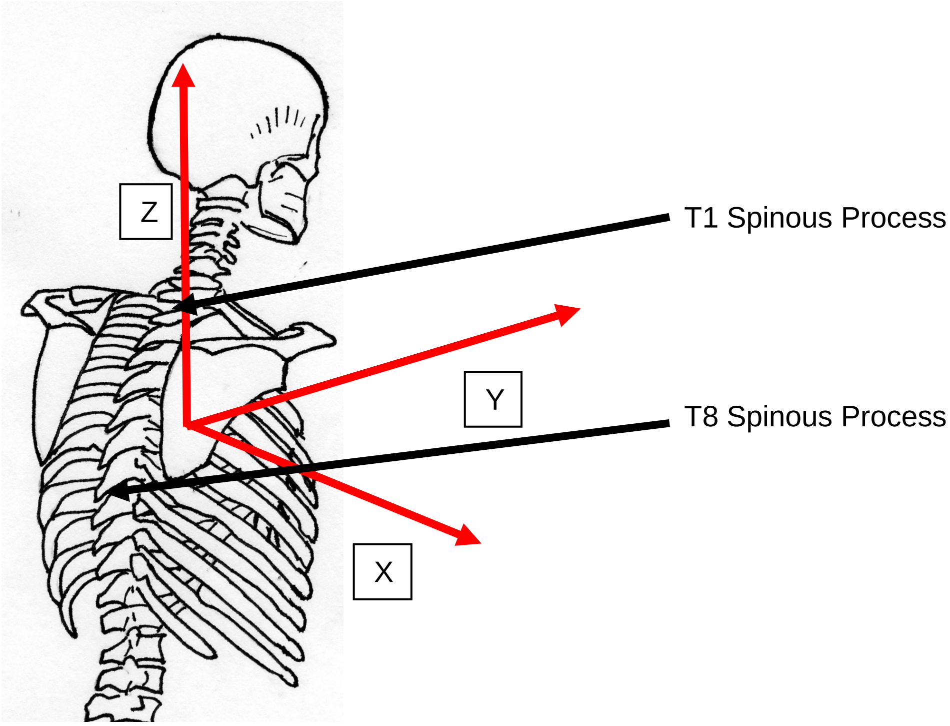


Figure 3.15. Thorax viewed from the front showing axis orientation.

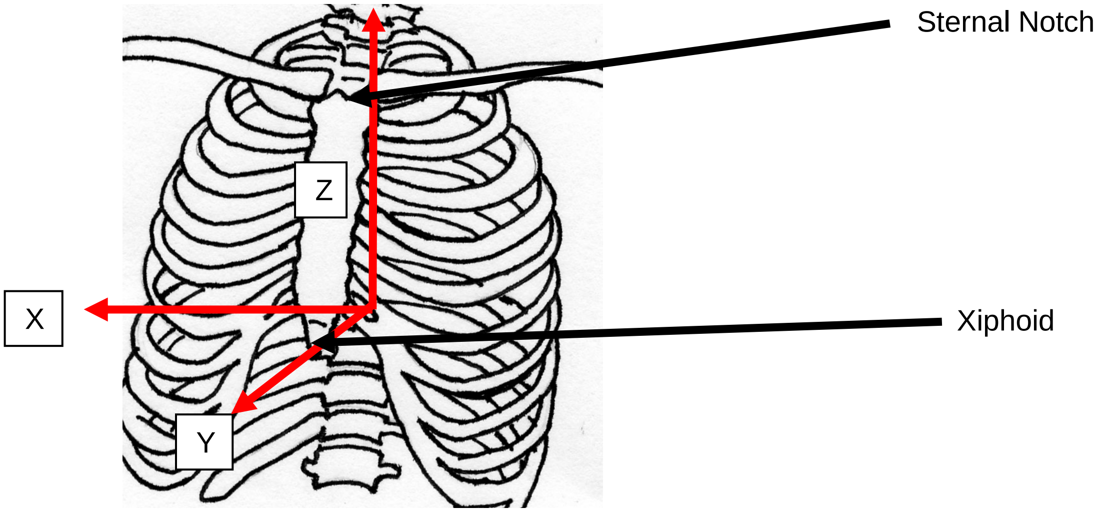


Figure 3.16. Postero-anterior view of the right scapula showing axis orientation.

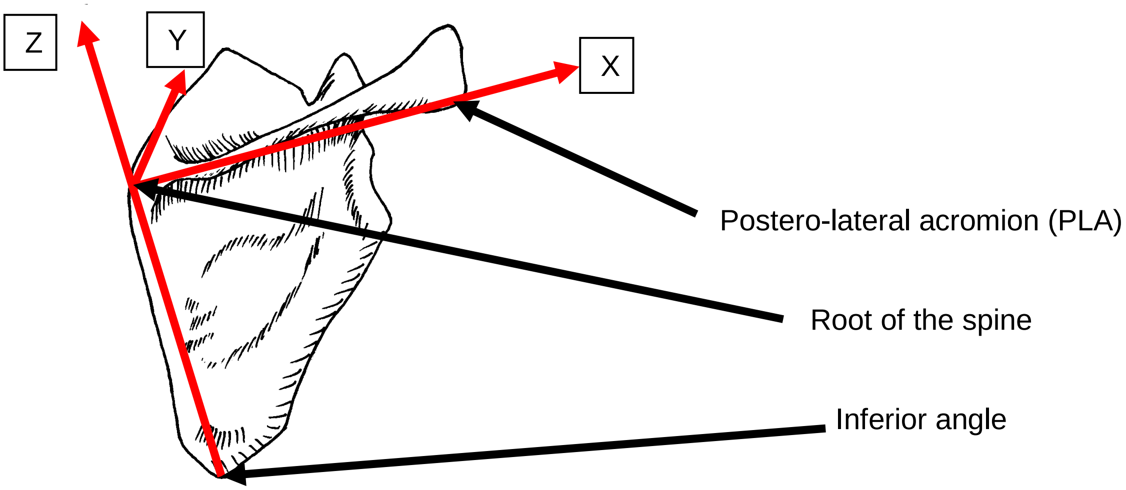


Figure 3.17. Superior view of the right scapula showing axis orientation. The “Z” axis is pointing directly at the observer.

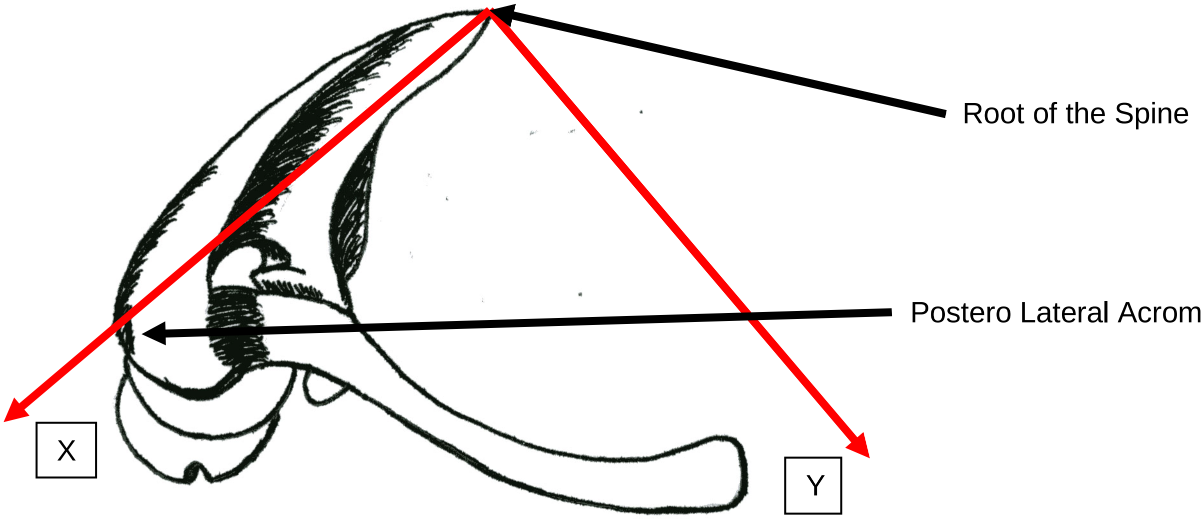


Figure 3.18. Coronal view of the right scapula from the right side showing axis orientation. The “X” axis is directed towards the observer.

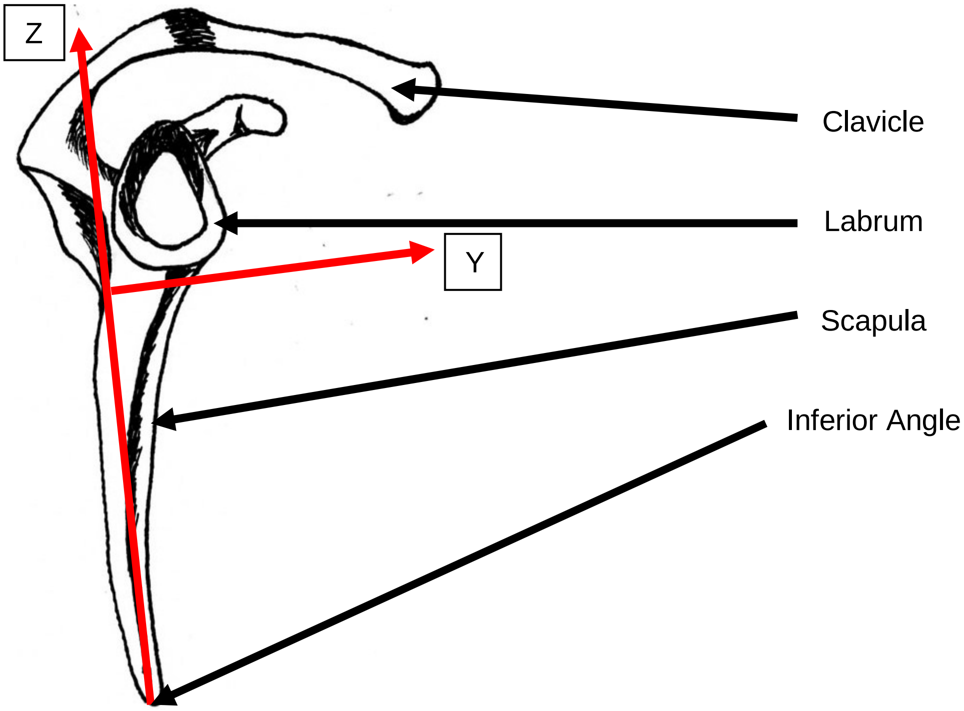
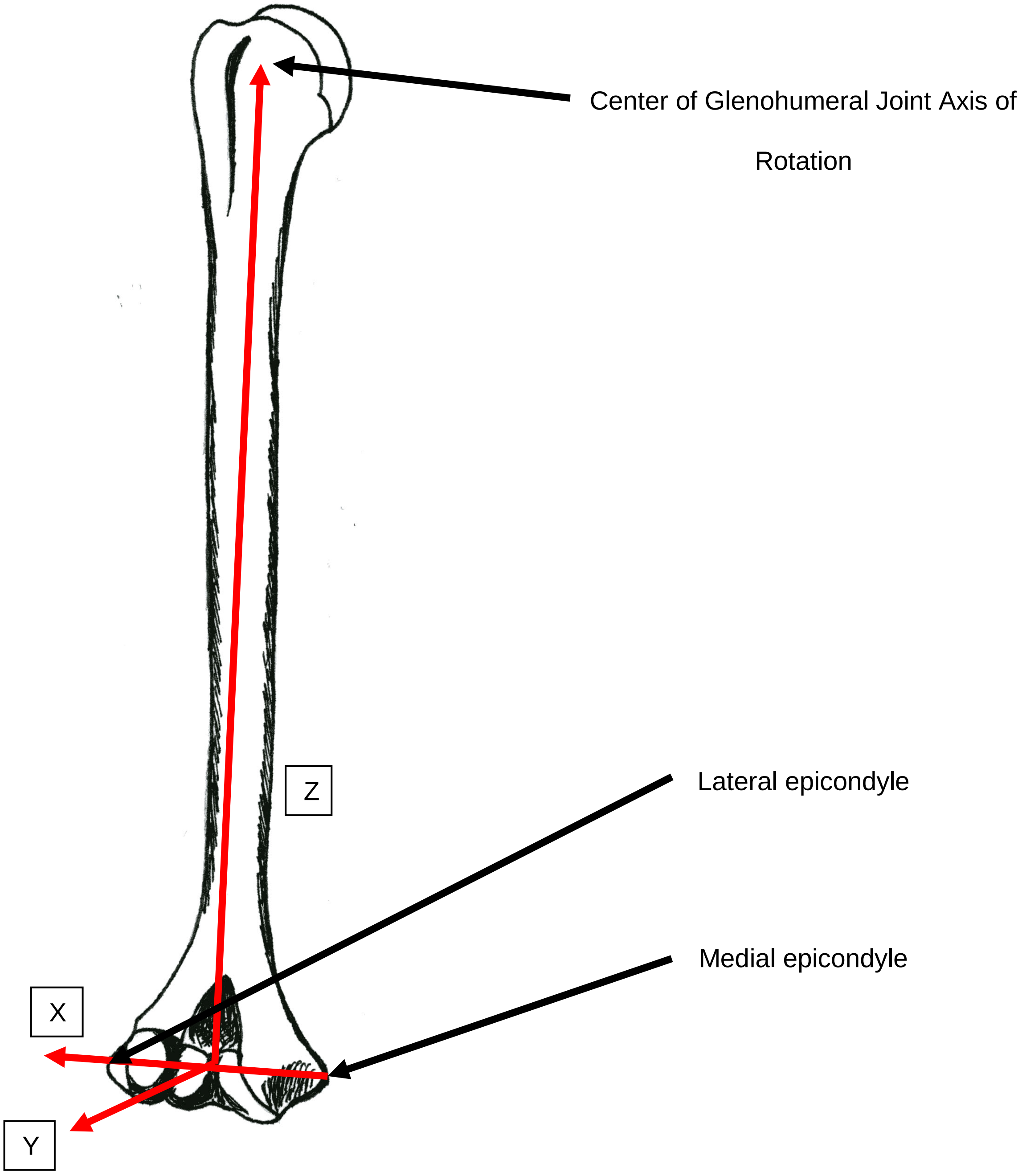


Figure 3.19. Right humerus viewed from the front showing axis orientation.



CHAPTER 4

RESULTS

Subjects

50 violinists were included in this study, 20 of whom were injured and 30 uninjured. Demographic information of the two groups is presented in Table 4.1. Five participants were omitted from the study. Participant 2 (injured group) was omitted since the extremes of motion at the scapula were physiologically impossible, possibly caused by movement of the kinematic sensors on the skin. Participants 9, 17 and 40 (all uninjured) presented with 2 or more impingement signs, yet reported no pain, and therefore did not fit into either the injured or uninjured groups. Kinematic data from participant 26 (injured) indicated possible gimbal lock singularity and kinematic data could not be used; data from subject 26 was therefore omitted from kinematic and EMG analysis. Serratus anterior data only from participant 16 (uninjured) was omitted because of an apparent misplacement of the electrode, resulting in performance EMG values being no different from resting values. The remainder of participant 16’s data was used in all analyses.

The majority of the participants in the study were female (n=36). Of the participants who were classified as injured, 17 (85%) were female and 3 (15%) were male. The average age for the injured group was 46.8 (± 3.5), and for the uninjured group was 37.1 (± 3.0), representing a significant difference (p=0.04).

No significant differences in terms of years of experience (p=0.12), or performance time per week (practice time (p=0.702), performance time (p=0.26), teaching time (p=0.46)) were evident, except that, of the 24 violinists that were professional musicians, 16 (67%) were injured and 8 (33%) were uninjured (p=0.0011) (Table H.1. Appendix H). Of the amateurs in the study, 2 were injured and 14 were uninjured. Of the musicians in the study that were students, 2 were injured and 8 were uninjured. The uninjured population of this study was recruited with apparent ease and was made up of 22 amateurs and students.

No significant differences were identified between the two groups in terms of past medical history (Appendix H, Table H.2). Two violinists from the injured group reported a past history of thoracic outlet syndrome, whereas none of the uninjured group reported such a history (p=0.08).

Physical Examination Results

As would be expected, injured musicians presented with limited range of shoulder motion on the right side compared to the uninjured musicians (see Table 4.2). Significant differences were noted for glenohumeral flexion (p<0.01), and glenohumeral abduction (p<0.01). Glenohumeral lateral and medial rotation (p=0.07 and 0.46 respectively) compared to uninjured participants did not reach a level of significance below 5%.

No significant differences in thoracic kyphosis in the standing position were noted between the two groups (p=0.35) (Table 4.3). As expected based on inclusion criteria, significant differences were seen between the two groups in terms of diagnostic test results, visual analog scale scores, and Shoulder Rating Questionnaire results (Table 4.4). No significant differences in instrument dimensions were identified between the two groups, (Table 4.4).

EVA Results

Introduction

EVA graphs for all dependent variables are presented in Figures 4.1 through 4.8. All EVA graphs are presented in the following arrangement:

Uninjured, Slow Performance	Uninjured, Fast Performance
Injured, Slow Performance	Injured, Fast Performance

For EVA analyses, as one moves from a graph on the left to the graph on the right (from slow to fast), the expectation, based on the remaining hypotheses, is to see higher odds ratios in the lower time period cells, i.e. cells 1, 2 or 3 and/or ratios less than 1 in cells 7,8, or 9. As one moves from uninjured towards injured (from the top to the bottom graph), the expectation, based on the proposed hypotheses, is that one could expect to see a shift in the direction of:

1. Higher Upper Trapezius amplitude (cells 3, 6, or 9).
2. Lower Serratus Anterior amplitude (cells 1, 4, or 7).
3. Higher amplitude for Scapula Upward Rotation, Scapula Internal Rotation, Glenohumeral Internal Rotation, and Glenohumeral Flexion (cells 3, 6, or 9).

4. Lower amplitude for Scapula Tilting and Glenohumeral Abduction (cells 1, 4, or 7).

5. A shift towards longer duration for any of these variables (high Time Period, cells 7, 8, or 9),

6. Or a combination of the above. For example, one may see a shift towards cell 9 (higher amplitude and longer time duration), or in the case of scapula tilting or glenohumeral abduction, a shift towards cell 7 (the worst case scenario for these two variables since lower kinematic rotations have been shown to be more closely associated with subacromial impingement syndrome).

In terms of the analysis of Speed, Injury and the interaction between Speed and Injury, information about the EVA changes with respect to fixed effects seen in the graphs can be explained by the odds ratios as follows:

Change	**Odds Ratio**
Uninjured Slow to Injured Slow	Injury
Uninjured Slow to Uninjured Fast	Speed
Injured Slow to Injured Fast	Speed X Interaction
Uninjured Fast to Injured Fast	Injury X Interaction

Note that odds ratios are multiplicative and therefore, for example, the odds ratio comparing injured slow to injured fast is the product of the odds ratio terms for speed and speed*injury interaction. Therefore, changes between groups may present a larger odds ratio than is immediately apparent.

Reliability of EVA Analysis

Intraclass correlation coefficients (ICC) [1,1] for kinematic variables are presented in Table 4.6. High ICCs (greater than 0.75, Portney and Watkins, 2000) were found in most cells of the kinematic and EMG variables (Table 4.6) and indicated a high level of reliability, with most values being greater than 0.75 for all EVA cells. Some lower values were found with upper trapezius and serratus anterior in cells 7 and 8, but this is likely because of the lower proportions of time that the EMG signal spent in low amplitude activation for sustained periods of time. Of the 144 possible cells in all 8 dependent variables, 123 (85%) were above 0.75, 13 (9%) were above 0.50 but below 0.75, and 3 (2%) were below 0.50. Five (3.5%) cells were empty.

Accordingly, the Standard Error of the Measurement analysis was performed, and values were found to be low for most cells in kinematic and EMG EVA arrays. Cells with zero values were not computable. Results are presented in Table 4.7. The results of these analyses suggest that the EVA method is reliable and therefore supports hypothesis 1.Of the 144 SEM measurements, 57 (39.6%) were below 5%, 70 (48.6%) were below 10% but above 5%, and 17 (11.8%) were above 10%. In some cases the proportion of the data represented in a cell may have been low and may have produced a low ICC. This may also have been impacted by the fact that to compute the ICC, the number of trials impacts the denominator and in cases where the mean square error is larger, the ICC may be low. In such cases, a low ICC and a low SEM may indicate that the measurement for that cell is moderately to highly repeatable.

Kinematic EVA Analysis

Kinematic variables were assessed separately for speed, and then further analysis followed for speed and injury effects. Lastly, speed was analyzed together with injury, age and gender to determine if results for injury and speed remain significant after adjustment for these baseline covariates.

Speed Effects

A shift in the direction of lower time period (higher frequency) was seen in all kinematic variables for the scapula and humerus, with higher odds ratios (OR) seen in cells 1, 2 or 3 compared to the reference cell (cell 5).

Scapula Tilting

Scapula Tilting EVA data are presented in Table H3 in Appendix H. Graphs illustrating scapula tilting EVAs are presented in Figure 4.1. Mixed Effects Multinomial Logistic Regression Analysis for speed is presented in Table 4.8. Significantly increased OR values were seen in cells 2, 3, and 6 (3.7, 8.8, and 4.2 respectively) ($p<0.05$). Significantly reduced OR values were seen in cells 4 and 7 (0.5 and 0.07), indicating a shift away from long duration and anterior tilting, and towards short duration posterior tilting when faster repertoire is played.

Visual observation of the EVA graphs for scapula tilting show a decrease in the height of cells 7 and 8, and an increase in size of cells 2 and 3, however, the effect of this trend may be affected by increases in the size of cell 5 in both injured and uninjured participants, although it does not appear that this change in cell 5 cancels out the decreases seen in cells 7 and 8, and increases seen in cells 2 and 3, since their change in magnitude proportionally exceeded that of cell 5.

Scapula Upward Rotation

Scapula Upward Rotation EVA data are presented in Table H4 in Appendix H Graphs illustrating scapula upward rotation EVAs are presented in Figure 4.2. Mixed Effects Multinomial Logistic Regression Analysis for speed is presented in Table 4.10. Significantly high OR values ($p<0.05$) were seen in cells 1, 2, 3 and 6 (5.8, 8.3, 6.3 and 2 respectively), while those for cells 7, 8 and 9 were all below 1 (0.05, 0.02 and 0.03 respectively). Observation of the graphs for uninjured and injured participants supports the statistically analyzed trends, with visual confirmation of increased height in cells 1, 2 and 3, and decreases in the size of cells 7, 8 and 9. These shifts indicate that the EVA graphs and statistical analysis represents the change in speed from slow to fast repertoire in both injured and uninjured participants.

Scapula Internal/External Rotation

Scapula Internal/External Rotation EVA data are presented in Table H5 in Appendix H. Graphs illustrating scapula internal/external rotation EVAs are presented in Figure 4.3. Mixed Effects Multinomial Logistic Regression Analysis for speed is presented in Table 4.12. Significantly high OR values were seen for the speed effect in cells 1, 2 and 3 (2.0, 3.9, and 3.0 respectively) ($p<0.05$). The EVA graphs for scapula internal/external rotation indicated increased height in cells 1, 2 and 3 for uninjured and injured participants, thereby confirming the trends seen in the statistical analysis. However, cell 5 was noted to decrease is size in both groups (17% in uninjured and 61% in injured groups), having the effect of increasing the likelihood of other cells increasing in magnitude. The increases seen in cells 1, 2 and 3 were close to or greater than 100%. High OR values were also seen in cells 4 and 7 and a very low OR in cell 9, but the magnitude of these changes, as seen in the graphs, was small compared to the changes seen in cell 5. The results of this analysis therefore suggest that the EVA was able to discern significant changes in cells that are representative of speed effects, namely increased magnitude in cells 1, 2 and 3.

Glenohumeral Flexion

Glenohumeral Flexion EVA data are presented in Table H6 in Appendix H. Graphs illustrating glenohumeral flexion EVAs are presented in Figure 4.4. Mixed Effects Multinomial Logistic Regression Analysis for speed is presented in Table 4.14. Significantly high OR values for cells 1, 2, and 3 (2.7, 3.0 and 2.4 respectively), and low OR were seen in cells 4, 6 and 9 (0.4, 0.3 and 0.01 respectively), suggesting that a trend towards higher speed was seen when fast repertoire was played. A high OR was seen for cell 7 (29.5), indicating a shift towards longer duration and less glenohumeral flexion as speed increased. The EVA graphs indicated increases in cells 1 and 2, although decreases in the size of cell 5 were seen for injured (-30%) and uninjured (-35%) participants. Cell 7 was noted to increase in size for both groups, more noticeably in the injured group.

Glenohumeral Abduction

Glenohumeral Abduction EVA data are presented in Table H7 in Appendix H. Graphs depicting the EVAs for glenohumeral abduction are presented in Figure 4.5. Mixed

Effects Multinomial Logistic Regression Analyses for speed are presented in Tables 4.16 (a and b). Several cells in the EVAs for this variable were at or close to zero (Table 4.16 (a)), resulting in very low point estimates for some of the cells in this analysis. Cells 7, 8 and 9 were therefore condensed into one (Table 4.16 (b)) for analysis of the effect of speed. In the condensed analysis (combined cells 7, 8 and 9), significantly high OR values were seen in cells 1 (28.9), 2 (23.7), and 3 (17.5), while low OR values were seen in the condensed cell combination for 7, 8 and 9. However, it should be noted that there was a 69% decrease in the magnitude of cell 5 for uninjured participants and a 75.5% decrease for injured participants, thus dampening the effects seen in Table 4.16 (b). Observation of the graphs for both injured and uninjured participants confirmed the trends towards higher proportions of the performance in cells 1, 2 and 3, with significant drops seen in cells 7, 8 and 9.

Cell 4 decreased (0.3) and cell 6 increased (1.8) indicating a shift towards less abduction at higher speeds, but these effects were within the margin of dampening effect seen in the reduction in cell 5. Therefore, the graphs and the statistical analysis suggest an overall shift towards higher frequency in both analyses for glenohumeral abduction.

Glenohumeral Internal/External Rotation

Glenohumeral Internal/External Rotation EVA data are presented in Table H8 in Appendix H. Graphs illustrating glenohumeral internal/external rotation EVAs are presented in Figure 4.6. Mixed Effects Multinomial Logistic Regression Analyses for speed are presented in Tables 4.18 (a and b). The standard error for cell 8 was zero and therefore cells 8 and 9 were combined and the logistic regression analysis was repeated (Table 4.18 (b)). In the condensed analysis (combining cells 8 and 9), significant decreases in OR values for cell 7 and combined cells 8 and 9 were seen (0.3 and 0.3), while significant increases were seen in cells 1 through 6. Visual observation of the graphs indicated that cell 5 decreased in magnitude (82%) in the uninjured group, but cells 1, 2 and 3 were noted to show marked increases in magnitude. In the injured group, cells 1 and 2 increased, and cell 9 was noted to increase. A marked drop in cell 5 (48%) was also noted.

Mixed Effects for Speed and Injury

Scapula Tilting

Scapula Tilting EVA data are presented in Table H3 in Appendix H. Graphs of scapula tilting EVAs are presented in Figure 4.1. Mixed Effects Multinomial Logistic Regression Analysis for injury is presented in Table 4.9. Statistical analysis indicates that significantly increased odds ratios for injury were seen in all cells except cells 1 and 4 for scapula tilting ($p<0.05$). However, the size of cell 5 decreased in both slow and fast trials, and since cell 5 is the reference cell for the analysis, this would have had a positive effect on the other cells in the array. Clear trends towards posterior tilting in the injury group were seen in cells 7 and 9, with a trend towards a decrease in cell 7 and an increase in cell 9 in both slow and fast trials as seen in the graphs. Statistical analysis indicated that the highest ratio (9.3) was seen in cell 9 for slow trials. A high OR was also seen in cell 7 (6.1), but this appears to have been influenced by a drop in cell 5. Analysis of the trend for injury in the performance of fast repertoire (injury odds ratio multiplied by the interaction effect) was high for cell 9 (25.1), also suggesting a significant shift towards posterior tilting. Therefore, the trends in both slow and fast trials are towards posterior tilting for longer duration, confirming the trends observed in the graphs.

Scapula Upward Rotation

Scapula Upward Rotation EVA data are presented in Table H4 in Appendix H. Graphs that illustrate the EVAs for scapula upward rotation are presented in Figure 4.2. Mixed Effects Multinomial Logistic Regression Analysis for injury is presented in Table 4.11. Significant decreases in OR were seen in cells 1, 4 and 7 (0.5, 0.4, and 0.4 respectively) at slow speeds ($p<0.05$). A low OR was also seen in cell 9 (0.2). However, an increase was also seen in cell 5 in the slow trials from 12.2 to 15.5 representing an increase of 27%. This would dampen the effect of the decrease seen in cells 1, 4 and 7, but probably not that of cell 9 to the same extent. Observation of the graphs for cells 1, 4 and 7 indicates decreases in height (% of performance duration) of half the magnitude of the increase seen in cell 5, while the drop in cell 9 was more pronounced, 3 times the magnitude of the difference seen in cell 5. This trend therefore represents increased upward scapular rotation for long durations at slow speeds in the injury group.

Analysis for high speed performance revealed significantly high OR in cells 4 and 7 (1.3 and 1.3), and low OR values for cells 6 (0.4) and 8 (0.3), indicating upward scapular rotation, and longer duration posturing at higher speeds in injured participants. This trend was visually confirmed in the graphs at cells 4, 6 and 8, but not at cell 7. A drop in OR of 0.14 was seen in cell 9 in the graph, but this was not significant ($p=0.62$). Observation of graph trends and the statistical analysis indicated increased upward scapular rotation in injured participants at fast speeds.

Scapula Internal/External Rotation

Scapula Internal/External Rotation EVA data are presented in Table H5 in Appendix H. Graphs illustrating kinematic EVA for scapula internal/external rotation are presented in Figure 4.3. Mixed Effects Multinomial Logistic Regression Analysis for injury is presented in Table 4.13. A significantly high OR for injury in cell 9 (15) at slow speeds, and at high speeds (4,500) was noted on statistical analysis. A statistically significant low OR was seen in cell 8 (0.3) at slow speed, confirming drop in cell 8 that was seen in the graph. High OR values were seen for all cells in the fast trials, most likely because of the 33% drop in cell 5 that was seen. Observation of the graphs for slow trials indicates that a significant proportion of time was spent at long duration mid-range internal rotation between 34 and 45 degrees (34% for slow trials and 29% for fast trials). This was significantly reduced in injured participants, with increases seen in cell 9 in both cases.

The trends that are seen for slow and fast speed performance suggest that injured participants adopt positions of greater internal rotation for longer durations when performing at both speeds.

Glenohumeral Flexion

Glenohumeral Flexion EVA data are presented in Table H6 in Appendix H. Graphs representing glenohumeral flexion EVA are presented in Figure 4.4. Mixed Effects Multinomial Logistic Regression Analysis for injury is presented in Table 4.15. Statistical analysis showed significantly increased OR values in cells 1, 2, 4, and 7 (1.6, 1.6, 3.8, and 32.3 respectively), while values below 1 were seen in cells 6, 8 and 9 (0.4, 0.6 and 0.08 respectively) for slow speed performance. This indicates that injured participants had a tendency to play with less glenohumeral flexion at slow speeds. Analysis of the effect of injury in fast performance indicated low OR values for cells 6 and 9, suggesting that injured participants played with decreased glenohumeral flexion at fast speeds as well. Furthermore, the results of both graphic as well as statistical results indicate that the position of less flexion was maintained for longer durations of time at fast speed.

Graphs the injured group suggest increases in cells 4 and 7, and decreases in cells 6 and 9 at slow speeds, and an increase in cell 7, with decreases in cells 8, 9 and 1 at fast speeds. This trend suggests a tendency to play in less glenohumeral flexion when injured.

Glenohumeral Abduction

Glenohumeral Abduction EVA data are presented in Table H7 in Appendix H. Graphs depicting the EVAs for glenohumeral abduction are presented in Figure 4.5. Mixed Effects Multinomial Logistic Regression Analyses for injury are presented in Tables 4.17 (a and b). Standard errors were zero for speed in cells 7 and 8, and it was decided to combine cells 7, 8 and 9 in a repeat analysis (Table 4.17(b)). In the analysis of combined cells 7, 8 and 9, there was a significant decrease in OR for combined cells 7, 8 and 9 (0.8) ($p<0.05$), but with the decrease in cell 5, this is not regarded as being a shift of clinical significance. Significant interactions for speed and injury were seen in cells 4 (1.2), 6 (0.65) and in combined cells 7, 8 and 9 (0.3). The shift in cell 6 was slight and probably not clinically significant. The shift in cell 4 is contrary to the observed change in the graph (the graph/EVA shows a decrease from 8% to 5%). Therefore, no notable changes in kinematics are seen across with respect to glenohumeral abduction.

An increase in the magnitude of cell 5 was seen in the slow trials, which would create a greater likelihood for these decreases to be seen Table 4.17 (b). This trend suggests a shift towards increased abduction and longer duration posturing in injured participants at slow speed, but the graph shows only a small decrease in cell 9 and a decrease in cell 7 as well, not necessarily supporting this trend.

At fast speed, the size of cell 5 stays the same, and there is a decrease in the magnitude of cell 9.

Glenohumeral internal/External Rotation

Glenohumeral Internal/External Rotation EVA data are presented in Table H8 in Appendix H. Graphs representing the EVAs for glenohumeral internal/external rotation are presented in Figure 4.6. Mixed Effects Multinomial Logistic Regression Analyses for injury are presented in Tables 4.19 (a and b). Standard errors for speed and interaction in cell 8, and for interaction in cell 9 were zero, indicating that the statistical analysis software could not estimate the odds ratio for these cells. Accordingly, cells 8 and 9 were combined and the statistical analysis was repeated. Results are presented in Table 4.19 (b). A significant decrease in OR was seen in cell 3 (0.4), while increases were seen in cells 1, 2, 4, 6, 7, and combined cells 8 and 9 (3, 2, 4, 2, 17 and 3 respectively), representing odds ratios for the effect of injury in slow trials. However, considering the 24% drop in cell 5, the effects for cells 1, 2, 3, 4 and 6 do not appear to be clinically significant. This leaves a significant and potentially relevant increase in cell 7, (towards longer duration). The OR for cells 8 and 9 was also higher, but not to the same extent as that of cell 7.

In the analysis for fast trials, decreased OR values for injury were seen in cells 1, 2 and 3 (0.5, 0.3 and 0.06 respectively), and combined cells 8 and 9 (34,000). Due to the increase in cell 5 of 126%, the increases seen in cells 4 and 7 are probably not clinically relevant, but those of cells 3, and combined cells 8 and 9 are, indicating a shift towards longer duration performance into external rotation at faster speeds.

Electromyography EVA Results

Preliminary analysis of normalized electromyography (EMG) signals for right upper trapezius (RUT) indicated consistent results in terms of minimum, mean, and median values. Standard deviations were, however, high compared to the means. Similar analysis for right serratus anterior (RSA) did not reveal the same consistency. It became evident that the mean RSA EMG for participant 16 for seated rest was almost the same as it was for the mean RSA relative voluntary electrical activity (RVE), which involved pushing against 4.55 kg force. This resulted in a high normalized RSA EMG (refer to the normalizing Formula 3.1 in Chapter 3), since the denominator in the normalizing equation was very low. Furthermore, the RSA EMG was not significantly different from the RSA value in the right upper trapezius (RUT) RVE task. These findings indicate that the RSA electrode was probably incorrectly placed on the fibers of the serratus anterior muscle for participant number 16. It was therefore decided to exclude RSA data for participant 16, a non-injured participant. Re-assessment of minimum, mean, and median values indicated consistent findings for remaining participants after participant 16 was excluded. Standard deviations for the remainder of the data were also low. Summary results for RSA and RUT EMG are presented in tables H.3 and H.4 in Appendix H.

Speed Effects

EMG EVA graphs are presented in Figures 4.7 and 4.8 for upper trapezius and serratus anterior respectively.

Upper Trapezius

Upper Trapezius EVA data are presented in Table H9 in Appendix H. Upper trapezius EMG EVA graphs are presented in Figure 4.7 and statistical analysis for speed effects is presented in Table 4.20. There was a decrease of 74% in magnitude seen for cell 5 for uninjured participants, and a 51% decrease for injured participants. Increases in OR values for cells 1, 2, 3 and 6 were seen (4.5 ($p<001$), 3.6 ($p<0.001$), 4.6 ($p<001$) and 5.8 ($p<0.001$) respectively), while a decrease was seen in cell 7 (0.2 ($p=0.03$)). All these changes appear to be of sufficient magnitude to be considered clinically relevant for speed effects in injured and uninjured participants, despite the drop in cell 5 seen for both groups.

Decreases in the magnitude of cells 4, 7, 8 and 9 were seen in the graphs for all participants from slow to fast repertoire, and increases were seen in cells 1, 3 and 6. Margin totals for Time Period from slow to fast repertoire in Table H9 (Appendix H) confirms the overall shift towards high short duration magnitude for injured and uninjured participants.

Serratus Anterior

Serratus Anterior EVA data are presented in Table H10 in Appendix H. Graphs that illustrate Serratus Anterior EMG EVAs are presented in Figure 4.8. Mixed-effects multinomial logistic regression analysis for speed effects is presented in Table 4.22. Cell 5 was noted to decrease by 88% in uninjured participants and by 91% in injured participants when moving from slow to fast repertoire. Statistical analysis showed increases in OR in cells 1, 2, 3, 6, and 9 (11 (p<0.01), 11 (p<0.01), 25 (p<0.01), 33 (p<0.01) and 19 (p<0.01) respectively.

The graphs showed that in the uninjured group cells 3 and 6 increased in magnitude, while cell 7 decreased, and in the injured group cells 3 and 6 increased in magnitude, while cells 4, 7 and 9 decreased. Margin totals (Table H.10, Appendix H) confirmed increases in the lower Time Period columns, while the upper Time Period column decreased.

Mixed Effects for Speed and Injury

Upper Trapezius

Upper Trapezius EVA data are presented in Table H9 in Appendix H. Graphs illustrating the EVAs for serratus anterior EMG are presented in Figure 4.8 and statistical analysis for mixed effects for speed and injury are presented in Table 4.21. The magnitude of cell 5 was noted to decrease by 47% for slow repertoire and it did not change for fast repertoire. In the slow repertoire, slight increases were seen in cells 1 and 9.

Statistical analysis indicated that cell 1 significantly increased in magnitude (2.4 (p=0.04) for slow repertoire indicating increased long duration lower amplitude activation in the upper trapezius of injured participants at slow speeds. For fast repertoire, significant interactions were seen in cells 6 and 9 (0.5 and 0.08 respectively) indicating slightly decreased long duration upper trapezius activation at fast speeds for injured participants. The amplitude margin totals did not change appreciably for slow repertoire, but the upper amplitude decreased, while the lower amplitude increased for fast repertoire (Table H.9, Appendix H).

Serratus Anterior

Serratus Anterior EVA data are presented in Table H10 in Appendix H. Graphs that illustrate the serratus anterior EMG EVAs are presented in Figure 4.8. Analysis for mixed effects multinomial logistic regression analysis for speed and injury are presented in Table 4.23. The magnitude of cell 5 was noted to decrease by 21% in the injured group. Significant increases in OR were seen in cell 6 and 9 (2.5 ($p=0.03$) and 2.4 ($p=0.02$) respectively, though this trend was not seen in visual inspection of the graph. For fast performance, the same trend was seen, though the effects were of slightly greater magnitude. These trends indicate increased long duration Serratus Anterior EMG activation in injured participants at slow and fast speeds. The EVA graphs indicate a shift towards shorter duration and lower amplitude activation of serratus anterior for injured participants playing slow repertoire, and the same for fast repertoire, although not to the same extent. Because of the visual observation of cell 9 being counter to that of the statistical analysis, it was ignored in terms of its effect on injured participants.

Summary of Hypothesis Testing

Hypothesis 1: Kinematic Analysis: supported, EMG Analysis: supported

Intraclass correlation coefficients (ICC) [1,1] for kinematic and EMG EVA analyses are presented in Table 4.6. High ICCs (Portney and Watkins, 2000) were determined for both kinematic and EMG EVA data, with the lowest EVA being 0.56 for scapula internal/external rotation in cell 4, and the highest being 0.99 for multiple cells in several variables. Standard Errors of the Measurement (SEM) values were also calculated and found to be 1.3 and 17% (Table 4.9). Therefore, the EVA was found to be reliable for both kinematic and EMG EVA methods.

Hypothesis 2: Supported

Significantly higher odds ratios (odds ratios greater than 1) were seen in cells 1, 2 and 3, and lower odds ratios (odds ratios below 1) were seen in cells 7, 8 and 9 in almost all kinematic EVA analyses for speed using mixed-effects multinomial logistic regression methods. Effects for speed were less noticeable for EMG analysis of Upper Trapezius and Serratus Anterior, possibly because of the frequency of activation compared to kinematic data. A speed effect was seen for upper trapezius, with cells 1, 2, 3 and 6 showing increased odds ratios (odds ratios greater than 1), while cells 7 and 8 were noted to decrease (lower than 1). A slight speed effect was also seen in Serratus Anterior recruitment with OR greater than 1 being present in cells 1, 2, and 3, with cells 6 and 9 also showing significant increases, therefore lessening the speed effect.

Hypothesis 3: Partially supported

Significant differences between injury groups were detected for upper trapezius EMG. Graphs depicting changes in EMG EVA for upper trapezius with respect to injury (comparing the top graph to the bottom graph for slow and fast repertoire (Figure 4.7)) demonstrated increased amplitude for Upper Trapezius at slow speed in cell 1, indicating greater low amplitude recruitment for short durations of time in slow repertoire, and a decrease in OR was seen in cells 6 and 9 in fast repertoire, also indicating less high amplitude, long duration activation, contrary to what was anticipated in this hypothesis. The hypothesis is therefore only partially supported for both slow and fast performance with respect to EMG amplitude, since the findings are significant, but in a different direction than was anticipated at the outset of this study.

Hypothesis 4: Partially supported

Significant differences between injury groups were detected for serratus anterior EMG. Graphs representing changes in EVA for Serratus Anterior EMG EVA are presented in Figure 4.8. Increased OR values were seen in cells 6 and 9 in both slow and fast repertoire in injured participants, contrary to what was hypothesized. This indicates that injured participants utilized increased long duration activation of the Serratus Anterior in the performance of slow and fast repertoire. The findings related to this hypothesis are therefore only partially supported, since the findings are significant, yet contrary to the direction anticipated at the start of the study.

Hypothesis 5: Partially supported.

Significant effects of injury were seen for all scapular kinematic variables. Shifts towards long duration posterior tilting were seen for slow and fast repertoire. Increased upward rotation for long durations of time were seen at slow and fast speeds. Internal rotation was seen to increase at both slow and fast speeds in injured participants. Therefore, injured musicians adopted longer duration posturing but scapula tilting and upward rotation motions were contrary to what was hypothesized. Musicians appeared to be moving in a compensatory fashion as a result of SIS, rather than these motions having a causal effect. Therefore, the hypothesis is partially supported due to the fact that these findings are significant clinically, but are not what was expected at the start of this study.

Hypothesis 6: Partially supported

Significant differences across injury groups were seen for glenohumeral kinematic variables. Injured musicians adopted longer durations in positions of less glenohumeral flexion contrary to what was hypothesized. They also adopted positions of increased external rotation, and for longer durations at faster speeds. These findings are contrary to what was hypothesized and also suggest that the injured musicians were moving in a compensatory fashion as a result of SIS, rather than these motions having a causal effect. The hypothesis is, however, partially supported since these findings are clinically significant.

Additional Analyses

1. None of the covariates that were examined (age, gender and arm plane elevation) were significantly correlated with the EMG and kinematic dependent variables in the analysis of arm elevation between 50 and 65 degrees (Tables H.14 to H.17, Appendix H). These covariates were examined because of significant differences that were seen in the summary statistics (Table 4.1). Results of the ANOVAs of arm elevation between 50 and 65 degrees are presented in tables 4.24 through 4.31 below. No injury main effects were found in any of the analyses. Significant speed effects were found for scapula tilting (p=0.026) and internal/external rotation (p=0.036), glenohumeral flexion (p<0.001), and for upper trapezius (p=0.002) and serratus anterior (p<0.001) EMG. A significant interaction was found for speed and injury for upper trapezius (p=0.036). Analysis of contrasts for slow and fast speeds indicated that there were no specific injury effects when speeds were analyzed independent of one another. Tables describing these analyses are presented in Tables H.18 and H.19 in Appendix H.

2. Scapula resting posture was compared between the two groups and no differences were identified in scapula tilting, upward rotation or internal/external rotation (Table 4.32).

3. Visually observed resting scapula alignment, classified as either “normal” or “abnormal”, and the kinematically determined scapula alignment, were compared using Fisher’s Exact Test. No significant correlations in any of the scapula resting postures were found (Tables H.11, H.12 and H.13, Appendix H).

4. In the analysis of raw data between 50 and 65 degrees of Arm Elevation, the measurement of various scapula variables was found to be reliable based on calculation of ICCs [3,1]. Reliability data for these measures are presented in table 4.33 below. ICCs for scapular kinematic data ranged from 0.88 to 0.99. Some glenohumeral measurements were found to have lower than anticipated reliability in some cases and high reliability in others. Glenohumeral flexion ICCs ranged from 0.73 to 0.92, abduction from 0.59 to 0.94, ad internal/external rotation from 0.88 to 0.99. EMG measurements demonstrated low to moderate levels of reliability, with ICCs ranging from 0.47 to 0.63 for upper trapezius, and 0.55 to 0.65 for serratus anterior. Various EMG time windows (5ms to 100ms) were separately analyzed for upper trapezius and serratus anterior and results were not dissimilar from those presented in table 4.33.

Figures and Tables

Table 4.1. Demographic makeup of the injured and uninjured groups. Data are presented as means and standard errors, or numbers and percentage prevalence in each group. p-values are based on Student's t-tests.

	Injured (n=20): Mean or n (SE or %)	**Uninjured (n=30): Mean or n (SE or %)**	**p-value**
Age	46.8 (3.5)	37.1 (3.0)	0.04*
Males	3 (15.0)	11 (36.7)	0.10
Females	17 (85.0)	19 (63.3)	0.10
Height (cm)	167.8 (1.4)	166.8 (1.9)	0.70
Weight (kg)	67.5 (2.7)	68.9 (2.2)	0.70
BMI	23.8 (0.7)	24.8 (0.7)	0.36

* Significant at the level $p \leq 0.05$ BMI is Body Mass Index

Table 4.2: Active Range of Shoulder Motion. Data are presented as means and standard errors of goniometric measurement. p-values are based on Student's t-tests.

Right Shoulder Motion	**Injured (n=20): Mean (SE)**	**Uninjured (n=30): Mean (SE)**	**p-value**
Shoulder Flexion	148.2 (4.9)	169.3 (1.2)	0.00*
Shoulder Abduction	144.9 (7.3)	177.2 (2.0)	0.00*
Shoulder External Rotation	77.1 (3.8)	84.5 (2.0)	0.07
Shoulder Internal Rotation	75.1 (2.0)	72.9 (1.9)	0.46

* Significant at the level $p \leq 0.05$

Table 4.3: Measurement of Thoracic Kyphosis. Data are presented as means and standard errors of inclinometric measurement. p-values are based on Student's t-tests.

	Injured (n=18): Mean (SE)	**Uninjured (n=28): Mean (SE)**	**p-value**
Thoracic Kyphosis (degrees)	46.7 (2.5)	43.7 (2.0)	0.35

Table 4.4 Diagnostic Test Results. Data are presented as means and standard errors, or numbers and percentage prevalence in each group. p-values are based on Student's t-tests.

Test		**Injured (n=20): Mean or n (SE or %)**	**Uninjured (n=30): Mean or n (SE or %)**	**p-value**
External Rotation:	MMT (0-5)	4.30 (0.1)	4.97 (0.03)	0.00*
	Pain (0-10)	15 (75.0)	0 (0.0)	0.00*
Internal Rotation	MMT(0-5)	4.60 (0.1)	4.97 (0.03)	0.00*
	Pain (0-10)	6 (30.0)	0 (0.0)	0.02*
Abduction	MMT(0-5)	4.35 (0.1)	5.00 (0.0)	0.00*
	Pain (0-10)	16 (80.0)	0 (0.0)	0.00*
Impingement Sign (0 or 1)	Neer	12 (60.0)	0 (0.0)	0.00*
	Jobe	18 (90.0)	0 (0.0)	0.00*
	Speed	14 (70.0)	0 (0.0)	0.00*
	Hawkins-Kennedy	17 (85.0)	10 (33.3)	0.00*
	Painful Arc	15 (75.0)	0 (0.0)	0.00*
Shoulder Rating Questionnaire (%)		72.5 (3.5)	95.6 (1.0)	0.00*
Visual Analogue Scale (0 to 10)		2.1 (0.5)	0.2 (0.1)	0.00*

MMT (Manual Muscle Test) graded 0-5, all scores were 4 or 5 regardless of injury status.

* Significant at the level $p \leq 0.05$

Table 4.5: Instrument Dimensions and Weight. Data are presented as means and standard errors of length and weight measurements. p-values are based on Student's t-tests.

Instrument Dimension	**Injured (n=20): Mean (SE)**	**Uninjured (n=30): Mean (SE)**	**p-value**
Total Length (mm)	613.2 (13.4)	602.6 (2.8)	0.34
Weight (kg)	0.5 (0.0)	0.5 (0.0)	0.80
Bridge to Scroll Length (mm)	327.7 (1.1)	326.0 (1.2)	0.33
Bridge Height (mm)	32.0 (0.3)	32.2 (0.2)	0.66
Bow Length (mm)	652.0 (1.3)	651.0 (0.7)	0.46
Active Neck Height (mm)	94.1 (2.5)	94.2 (2.0)	0.97

Table 4.6. Intraclass Correlation Coefficients [1,1] (ICC) of dependent variables for all EVA data. ICCs between 0.50 and 0.75 are regarded as denoting “moderate reliability” and are presented in bold type, and ICCs above 0.75 are regarded as denoting “high reliability” and are presented in bold type and are underlined (Portney and Watkins (2000)).

		EVA Cell								
Dependent Variable	**Speed**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Scapula Tilting	Slow	**0.73**	**0.66**	**0.65**	0.47	**0.65**	**0.78**	**0.96**	**0.85**	**0.94**
	Fast	**0.58**	**0.61**	**0.70**	**0.69**	**0.77**	**0.67**	**0.88**	**0.74**	**0.85**
Scapula Upward Rotation	Slow	**0.56**	**0.71**	**0.74**	**0.79**	**0.61**	**0.79**	**0.93**	**0.86**	**0.97**
	Fast	**0.85**	**0.81**	**0.88**	**0.73**	**0.59**	**0.64**	**0.82**	**0.64**	**0.99**
Scapula Int./Ext. Rotation	Slow	**0.65**	**0.68**	**0.82**	**0.77**	**0.75**	**0.67**	**0.95**	**0.83**	**0.87**
	Fast	**0.56**	**0.58**	**0.79**	0.39	0.43	**0.65**	**0.94**	**0.64**	**0.95**
GHJ Flexion	Slow	**0.73**	**0.80**	**0.88**	**0.91**	**0.85**	**0.91**	**0.93**	**0.84**	**0.98**
	Fast	**0.89**	**0.86**	**0.88**	**0.86**	**0.85**	0.48	**0.96**	**0.90**	**0.95**
GHJ Abduction	Slow	**0.54**	**0.68**	**0.61**	**0.82**	**0.57**	**0.57**	**0.91**	**0.72**	**0.90**
	Fast	**0.86**	**0.83**	**0.93**	**0.74**	**0.72**	**0.88**	-	-	**0.90**
GHJ Int./Ext. Rotation	Slow	**0.76**	**0.80**	**0.72**	0.39	0.43	**0.86**	**0.95**	**0.85**	**0.98**
	Fast	**0.96**	**0.93**	**0.90**	**0.85**	**0.86**	**0.85**	**0.98**	-	**0.99**
Upper Trapezius	Slow	0.42	**0.70**	**0.61**	**0.73**	**0.74**	**0.83**	**0.84**	**0.85**	**0.90**
	Fast	**0.65**	**0.80**	**0.73**	**0.74**	**0.78**	**0.84**	**0.87**	**0.67**	**0.97**
Serratus Anterior	Slow	**0.80**	**0.83**	**0.78**	**0.85**	**0.87**	**0.86**	**0.96**	**0.87**	**0.71**
	Fast	**0.87**	**0.89**	**0.89**	**0.89**	**0.79**	**0.90**	**0.96**	0.42	**0.88**

* Hyphens represent EVA cells that had zero values.

Table 4.7. Standard Error of the Mean (SEM) (%) for dependent variables for all EVA data.

		EVA Cell								
Dependent Variable	**Speed**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Scapula Tilting	Slow	2.0	2.7	2.2	6.4	8.7	5.6	7.8	13.6	11.7
	Fast	4.5	7.8	6.4	7.7	11.4	8.4	13.4	17.0	14.8
Scapula Upward Rotation	Slow	1.7	2.3	1.5	5.1	7.1	3.8	8.8	11.3	6.3
	Fast	5.8	7.5	4.5	9.4	14.1	7.8	12.4	13.9	2.3
Scapula Int./Ext. Rotation	Slow	2.1	3.6	2.1	5.6	5.1	4.5	6.9	5.6	5.1
	Fast	6.0	9.8	6.5	7.0	14.9	7.5	9.9	24.2	8.0
GHJ Flexion	Slow	2.1	3.7	2.2	5.6	6.5	4.0	5.4	5.0	4.2
	Fast	4.4	7.5	5.0	6.4	8.2	6.1	8.4	6.3	5.7
GHJ Abduction	Slow	1.8	3.3	1.9	4.8	7.5	4.8	7.0	7.6	7.4
	Fast	6.4	5.6	3.9	8.4	6.4	6.9	-	-	5.8
GHJ Int./Ext. Rotation	Slow	2.1	3.6	2.1	5.6	5.1	4.5	6.9	5.6	5.1
	Fast	4.7.	5.8	4.7	5.7	4.5	7.0	3.2	-	1.3
Upper Trapezius	Slow	4.8	5.1	6.4	4.0	4.4	6.8	3.1	1.7	7.8
	Fast	4.5	3.8	5.6	4.8	2.5	8.0	1.7	-	7.6
Serratus Anterior	Slow	3.4	3.8	4.4	2.9	4.0	7.2	2.9	2.7	5.9
	Fast	2.3	2.8	5.4	1.6	1.7	8.5	0.2	-	6.8

* Hyphens represent EVA cells that had zero values.

Table 4.8. Mixed Effects Multinomial Logistic Regression Analysis for Scapula Tilting Kinematic EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	**Effect**	**Estimate**	**Standard Error**	**p-Value**	**Odds Ratio**	**Lower 5%**	**Upper 95%**
1	Speed	-0.307	0.184	0.095	0.735	0.513	1.055
2	Speed	1.293	0.191	0.000	**3.646**	2.507	5.303
3	Speed	2.178	0.248	0.000	**8.829**	5.432	14.350
4	Speed	-0.767	0.207	0.000	**0.469**	0.313	0.704
6	Speed	1.424	0.277	0.000	**4.153**	2.415	7.143
7	Speed	-2.613	0.257	0.000	**0.073**	0.044	0.121
8	Speed	-0.220	0.270	0.416	0.803	0.473	1.363
9	Speed	-0.229	0.347	0.510	0.796	0.403	1.571

Table 4.9. Mixed Effects Multinomial Logistic Regression Analysis for Scapula Tilting Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-1.119	0.161	0.000	**0.327**	0.238	0.448
	Speed	-0.474	0.209	0.023	**0.622**	0.413	0.937
	Injury	0.326	0.315	0.183	1.385	0.857	2.237
	Interaction	0.231	0.245	0.462	1.260	0.680	2.336
2	Intercept	-0.851	0.148	0.000	**0.427**	0.320	0.570
	Speed	1.193	0.190	0.000	**3.297**	2.271	4.786
	Injury	1.046	0.275	0.000	**2.848**	1.832	4.427
	Interaction	-0.125	0.225	0.648	0.882	0.515	1.511
3	Intercept	-2.366	0.216	0.000	**0.094**	0.062	0.143
	Speed	1.886	0.256	0.000	**6.595**	3.997	10.882
	Injury	1.075	0.308	0.000	**2.931**	1.604	5.354
	Interaction	0.371	0.378	0.327	1.445	0.691	3.040
4	Intercept	-0.503	0.143	0.000	**0.605**	0.457	0.800
	Speed	-0.698	0.207	0.001	**0.498**	0.332	0.747
	Injury	0.833	0.224	0.000	**2.300**	1.482	3.570
	Interaction	-0.582	0.304	0.056	0.559	0.308	1.015
6	Intercept	-2.916	0.236	0.000	**0.054**	0.034	0.086
	Speed	1.240	0.251	0.000	**3.454**	2.112	5.650
	Injury	1,333	0.256	0.000	**3.794**	2.295	6.271
	Interaction	0.558	0.390	0.153	1.746	0.813	3.752
7	Intercept	-0.457	0.167	0.006	**0.633**	0.456	0.879
	Speed	-2.763	0.269	0.000	**0.063**	0.037	0.107
	Injury	1.810	0.241	0.000	**6.107**	3.812	9.785
	Interaction	0.229	0.362	0.528	1.257	0.618	2.558
8	Intercept	-0.740	0.149	0.000	**0.477**	0.357	0.639
	Speed	-0.489	0.181	0.007	**0.613**	0.430	0.874
	Injury	1.002	0.185	0.000	**2.723**	1.897	3.909
	Interaction	-0.005	0.279	0.986	0.995	0.576	1.719
9	Intercept	-11.406	0.562	0.000	**0.000**	0.000	0.000
	Speed	1.543	0.316	0.000	**4.679**	2.521	8.687
	Injury	2.223	0.283	0.000	**9.269**	5.319	16.150
	Interaction	0.996	0.503	0.048	**2.708**	1.010	7.263

Table 4.10. Mixed Effects Multinomial Logistic Regression Analysis for Scapula Upward Rotation Kinematic EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	**Effect**	**Estimate**	**Standard Error**	**p-Value**	**Odds Ratio**	**Lower 5%**	**Upper 95%**
1	Speed	1.753	0.154	0.000	**5.772**	4.268	7.805
2	Speed	2.121	0.152	0.000	**8.340**	6.193	11.230
3	Speed	1.834	0.187	0.000	**6.258**	4.340	9.024
4	Speed	0.047	0.171	0.785	1.048	0.749	1.465
6	Speed	0.700	0.235	0.003	**2.014**	1.271	3.192
7	Speed	-3.038	0.256	0.000	**0.048**	0.029	0.079
8	Speed	-3.805	0.179	0.000	**0.023**	0.016	0.032
9	Speed	-1.297	0.000	-	0.027	-	-

Table 4.11. Mixed Effects Multinomial Logistic Regression Analysis for Scapula Upward Rotation Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-1.548	0.147	0.000	**0.213**	0.160	0.284
	Speed	0.736	0.182	0.000	**2.088**	1.462	2.981
	Injury	-0.725	0.270	0.002	**0.484**	0.305	0.770
	Interaction	0.781	0.236	0.004	**2.184**	1.286	3.708
2	Intercept	-1.426	0.141	0.000	**0.240**	0.182	0.317
	Speed	1.744	0.170	0.000	**5.718**	4.099	7.976
	Injury	-0.188	0.213	0.303	0.829	0.580	1.185
	Interaction	0.297	0.182	0.162	1.346	0.887	2.043
3	Intercept	-2.713	0.266	0.000	**0.066**	0.039	0.112
	Speed	1.679	0.286	0.000	**5.360**	3.057	9.395
	Injury	0.120	0.330	0.667	1.127	0.654	1.943
	Interaction	0.324	0.278	0.326	1.383	0.725	2.640
4	Intercept	0.064	0.163	0.694	1.066	0.775	1.466
	Speed	-2.262	0.261	0.000	**0.104**	0.063	0.174
	Injury	-1.044	0.192	0.000	**0.352**	0.242	0.513
	Interaction	1.375	0.273	0.000	**3.954**	2.315	6.754
6	Intercept	-3.528	0.548	0.000	**0.029**	0.010	0.086
	Speed	1.087	0.426	0.011	**2.966**	1.288	6.831
	Injury	0.259	0.354	0.465	1.295	0.647	2.592
	Interaction	-1.160	0.452	0.010	**0.314**	0.129	0.761
7	Intercept	-0.339	0.173	0.050	**0.713**	0.508	1.000
	Speed	-3.275	0.291	0.000	**0.038**	0.021	0.067
	Injury	-1.035	0.182	0.000	**0.355**	0.248	0.508
	Interaction	1.317	0.290	0.000	**3.732**	2.113	6.591
8	Intercept	-1.140	0.285	0.000	**0.320**	0.183	0.559
	Speed	-0.837	0.313	0.008	**0.433**	0.234	0.800
	Injury	0.318	0.269	0.238	1.374	0.811	2.329
	Interaction	-1.458	0.333	0.000	**0.233**	0.121	0.447
9	Intercept	-7.165	0.708	0.000	**0.001**	0.000	0.003
	Speed	-0.871	0.596	0.144	0.418	0.130	1.346
	Injury	-1.601	0.520	0.002	**0.202**	0.073	0.559
	Interaction	-0.342	0.683	0.617	0.711	0.186	2.710

Table 4.12. Mixed Effects Multinomial Logistic Regression Analysis for Scapula Internal External Rotation Kinematic EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	**Effect**	**Estimate**	**Standard Error**	**p-Value**	**Odds Ratio**	**Lower 5%**	**Upper 95%**
1	Speed	0.696	0.197	0.000	**2.005**	1.363	2.951
2	Speed	1.349	0.110	0.000	**3.855**	3.110	4.779
3	Speed	1.089	0.127	0.000	**2.970**	2.317	3.807
4	Speed	-0.794	0.160	0.000	**4.522**	0.330	0.619
6	Speed	-0.099	0.165	0.549	0.906	0.653	1.252
7	Speed	0.779	0.157	0.000	**2.179**	1.603	2.962
8	Speed	0.210	0.138	0.128	1.234	0.942	1.616
9	Speed	-4.961	0.419	0.000	**0.007**	0.003	0.016

Table 4.13. Mixed Effects Multinomial Logistic Regression Analysis for Scapula Internal/External Rotation Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-2.097	0.203	0.000	**0.123**	0.083	0.183
	Speed	1.662	0.257	0.000	**5.270**	3.184	8.724
	Injury	0.058	0.278	0.836	1.060	0.614	1.827
	Interaction	1.315	0.365	0.000	**3.724**	1.822	7.614
2	Intercept	-1.144	0.135	0.000	**0.319**	0.244	0.415
	Speed	1.757	0.193	0.000	**5.796**	3.970	8.462
	Injury	0.292	0.183	0.109	1.340	0.937	1.916
	Interaction	1.392	0.265	0.000	**4.024**	2.392	6.769
3	Intercept	-2.284	0.155	0.000	**0.102**	0.075	0.138
	Speed	1.234	0.188	0.000	**3.435**	2.374	4.968
	Injury	-0.203	0.184	0.270	0.816	0.570	1.170
	Interaction	1.170	0.264	0.000	**3.221**	1.920	5.404
4	Intercept	-1.498	0.175	0.000	**0.224**	0.159	0.315
	Speed	-0.452	0.249	0.070	0.636	0.391	1.036
	Injury	0.082	0.204	0.690	1.085	0.727	1.612
	Interaction	2.074	0.354	0.000	**7.954**	3.978	15.906
6	Intercept	-3.697	0.224	0.000	**0.025**	0.016	0.039
	Speed	0.254	0.243	0.295	1.290	0.801	2.076
	Injury	-0.007	0.211	0.973	0.993	0.657	1.500
	Interaction	2.117	0.338	0.000	**8.305**	4.283	16.102
7	Intercept	-5.895	0.340	0.000	**0.003**	0.001	0.001
	Speed	-1.130	0.275	0.000	**0.323**	0.188	0.554
	Injury	0.345	0.260	0.185	1.412	0.848	2.353
	Interaction	3.631	0.411	0.000	**37.758**	16.866	84.532
8	Intercept	0.302	0.114	0.008	**1.353**	1.081	1.692
	Speed	-1.163	0.157	0.000	**0.312**	0.230	0.425
	Injury	-1.312	0.142	0.000	**0.269**	0.204	0.356
	Interaction	0.638	0.237	0.007	**1.893**	1.188	3.014
9	Intercept	-6.385	0.304	0.000	**0.002**	0.001	0.003
	Speed	-2.537	0.354	0.000	**0.079**	0.040	0.158
	Injury	2.723	0.260	0.000	**15.220**	9.159	25.292
	Interaction	5.700	0.447	0.000	**298.768**	124.480	717.083

Table 4.14. Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Flexion Kinematic EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Speed	1.008	0.122	0.000	**2.741**	2.157	3.483
2	Speed	1.098	0.077	0.000	**2.999**	2.581	3.485
3	Speed	0.806	0.108	0.000	**2.239**	1.812	2.767
4	Speed	-1.195	0.192	0.000	**0.303**	0.208	0.441
6	Speed	-0.989	0.158	0.000	**0.372**	0.273	0.506
7	Speed	3.386	0.167	0.000	**29.536**	21.307	40.942
8	Speed	0.129	0.211	0.540	1.138	0.752	1.722
9	Speed	-4.721	0.509	0.000	**0.009**	0.003	0.024

Table 4.15. Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Flexion Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-1.803	0.093	0.000	**0.165**	0.137	0.198
	Speed	2.519	0.137	0.000	**12.418**	9.496	16.238
	Injury	0.491	0.147	0.000	**1.634**	1.245	2.179
	Interaction	0.069	0.201	0.732	1.071	0.723	1.588
2	Intercept	-0.557	0.060	0.000	**0.573**	0.510	0.645
	Speed	1.674	0.103	0.000	**5.333**	4.355	6.530
	Injury	0.479	0.096	0.000	**1.615**	1.337	1.950
	Interaction	-0.081	0.140	0.562	0.922	0.701	1.213
3	Intercept	-1.056	0.071	0.000	**0.348**	0.303	0.400
	Speed	-0.780	0.146	0.000	**0.458**	0.344	0.611
	Injury	-0.117	0.117	0.321	0.890	0.707	1.120
	Interaction	-0.118	0.182	0.516	0.888	0.621	1.270
4	Intercept	-1.497	0.089	0.000	**0.234**	0.188	0.266
	Speed	1.426	0.152	0.000	**4.162**	3.089	5.608
	Injury	1.346	0.103	0.000	**3.843**	3.140	4.703
	Interaction	0.023	0.235	0.924	1.023	0.645	1.621
6	Intercept	-0.598	0.066	0.000	**0.550**	0.483	0.626
	Speed	-3.470	0.216	0.000	**0.031**	0.020	0.078
	Injury	-0.818	0.122	0.000	**0.441**	0.348	0.560
	Interaction	0.711	0.249	0.004	**2.037**	1.249	3.321
7	Intercept	-6.990	0.216	0.000	**0.001**	0.001	0.001
	Speed	2.435	0.185	0.000	**11.420**	7.942	16.420
	Injury	3.475	0.155	0.000	**32.312**	28.832	43.808
	Interaction	-0.339	0.311	0.275	0.712	0.387	1.310
8	Intercept	-2.817	0.134	0.000	**0.060**	0.046	0.078
	Speed	0.315	0.240	0.190	1.370	0.855	2.193
	Injury	-0.472	0.154	0.002	**0.624**	0.461	0.843
	Interaction	-0.321	0.372	0.389	0.726	0.350	1.505
9	Intercept	-11.221	0.461	0.000	**0.000**	0.000	0.000
	Speed	-0.014	0.295	0.962	0.986	0.554	1.757
	Injury	-2.454	0.327	0.000	**0.086**	0.045	0.163
	Interaction	-2.221	1.045	0.034	**0.109**	0.014	0.842

Table 4.16 (a). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Abduction Kinematic EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Speed	4.240	0.165	0.000	**69.386**	50.250	95.811
2	Speed	4.323	0.151	0.000	**75.402**	56.107	101.332
3	Speed	4.472	0.162	0.000	**87.565**	63.802	120.180
4	Speed	-1.145	0.202	0.000	**0.318**	0.214	0.472
6	Speed	3.610	0.173	0.000	**39.956**	26.326	51.879
7	Speed	-41.000	-	-	0.000	-	-
8	Speed	-40.734	-	-	0.000	-	-
9	Speed	-0.584	0.257	0.023	**0.558**	0.337	0.922

Table 4.16 (b). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Abduction Kinematic EVA: analysis for speed only, with cells 7, 8 and 9 combined. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cells	**Effect**	**Estimate**	**Standard Error**	**p-Value**	**Odds Ratio**	**Lower 5%**	**Upper 95%**
1	Speed	3.365	0.108	0.000	**28.930**	23.422	35.732
2	Speed	3.169	0.088	0.000	**23.794**	20.022	28.276
3	Speed	2.859	0.109	0.000	**17.451**	14.084	21.621
4	Speed	-1.104	0.155	0.000	**0.332**	0.245	0.450
6	Speed	0.572	0.149	0.000	**1.772**	1.323	2.375
7, 8, and 9	Speed	-7.186	0.341	0.000	**0.001**	0.000	0.002

Table 4.17 (a). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Abduction Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	**Effect**	**Estimate**	**Standard Error**	**p-Value**	**Odds Ratio**	**Lower 5%**	**Upper 95%**
1	Intercept	-2.403	0.104	0.000	**0.090**	0.074	0.111
	Speed	3.307	0.159	0.000	**27.295**	19.980	37.288
	Injury	-0.090	0.164	0.587	0.915	0.664	1.261
	Interaction	0.055	0.180	0.759	1.057	0.743	1.502
2	Intercept	-1.050	0.064	0.000	**0.350**	0.309	0.397
	Speed	3.273	0.137	0.000	**26.397**	20.180	34.531
	Injury	-0.393	0.116	0.001	**0.675**	0.538	0.847
	Interaction	0.140	0.144	0.331	1.151	0.867	1.527
3	Intercept	-2.006	0.089	0.000	**0.135**	0.113	0.160
	Speed	3.288	0.155	0.000	**26.796**	19.786	36.290
	Injury	-0.413	0.141	0.004	**0.663**	0.503	0.873
	Interaction	0.092	0.180	0.612	1.096	0.700	1.560
4	Intercept	-0.925	0.069	0.000	**0.397**	0.346	0.455
	Speed	-0.976	0.206	0.000	**0.377**	0.252	0.564
	Injury	0.966	0.138	0.000	**2.628**	2.003	3.447
	Interaction	-1.057	0.215	0.000	**0.347**	0.228	0.529
6	Intercept	-2.051	0.085	0.000	**0.129**	0.109	0.152
	Speed	1.950	0.161	0.000	**7.027**	5.127	9.632
	Injury	-0.916	0.122	0.000	**0.400**	0.315	0.508
	Interaction	-0.401	0.197	0.042	**0.670**	0.455	0.986
7	Intercept	-2.377	0.128	0.000	**0.093**	0.072	0.119
	Speed	-40.598	0.000	-	0.000	-	-
	Injury	0.935	0.205	0.000	**2.548**	1.703	3.810
	Interaction	-1.211	0.000	-	0.298	-	-
8	Intercept	-0.971	0.068	0.000	**0.379**	0.332	0.432
	Speed	-40.338	0.000	-	0.000	-	-
	Injury	-0.498	0.105	0.000	**0.608**	0.495	0.747
	Interaction	-1.319	0.000	-	0.268	-	-
9	Intercept	-4.365	0.156	0.000	**0.013**	0.009	0.017
	Speed	-6.157	0.425	0.000	**0.002**	0.001	0.005
	Injury	-2.614	0.117	0.000	**0.073**	0.058	0.092
	Interaction	-3.897	0.425	0.000	**0.020**	0.009	0.047

Table 4.17 (b). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Abduction Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury, with cells 7, 8 and 9 combined. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-2.176	0.097	0.000	**0.114**	0.094	0.137
	Speed	3.532	0.151	0.000	**34.201**	25.445	45.970
	Injury	0.073	0.140	0.601	1.076	0.817	1.417
	Interaction	0.100	0.191	0.600	1.105	0.760	1.607
2	Intercept	-0.923	0.063	0.000	**0.397**	0.351	0.450
	Speed	3.535	0.134	0.000	**34.303**	26.382	44.601
	Injury	0.038	0.094	0.505	1.038	0.864	1.248
	Interaction	-0.116	0.174	0.688	0.891	0.634	1.252
3	Intercept	-1.743	0.086	0.000	**0.175**	0.148	0.207
	Speed	3.362	0.162	0.000	**28.859**	21.018	39.624
	Injury	0.162	0.126	0.200	1.176	0.918	1.505
	Interaction	-0.266	0.217	0.220	0.767	0.501	1.173
4	Intercept	-0.977	0.065	0.000	**0.376**	0.332	0.427
	Speed	0.830	0.180	0.000	**0.436**	0.306	0.621
	Injury	0.185	0.083	0.892	1.203	1.022	1.415
	Interaction	-0.024	0.178	0.026	**0.976**	0.689	1.383
6	Intercept	-1.401	0.073	0.000	**0.246**	0.214	0.284
	Speed	1.304	0.221	0.000	**3.683**	2.388	5.679
	Injury	0.113	0.102	0.269	1.119	0.916	1.367
	Interaction	-0.544	0.269	0.043	**0.581**	0.343	0.984
7, 8 and 9	Intercept	0.685	0.045	0.000	**1.994**	1.817	2.167
	Speed	-5.036	0.381	0.000	**0.006**	0.003	0.014
	Injury	-0.182	0.652	0.005	**0.833**	0.187	0.947
	Interaction	-0.973	0.358	0.007	**0.378**	0.733	0.763

Table 4.18 (a). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Internal/External Rotation Kinematic EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Speed	4.472	0.173	0.000	**87.522**	62.371	122.817
2	Speed	4.255	0.162	0.000	**70.454**	51.303	96.754
3	Speed	3.186	0.186	0.000	**24.180**	16.802	34.798
4	Speed	0.731	0.209	0.000	**2.077**	1.378	3.129
6	Speed	-0.073	0.735	0.921	0.930	0.220	3.927
7	Speed	-0.204	0.235	0.385	0.815	0.515	1.292
8	Speed	-40.012	0.000	-	0.000	-	-
9	Speed	-0.898	1.494	0.548	0.407	0.022	7.619

Table 4.18 (b). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Internal/External Rotation Kinematic EVA: analysis for speed only, with cells 8 and 9 combined. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	**Effect**	**Estimate**	**Standard Error**	**p-Value**	**Odds Ratio**	**Lower 5%**	**Upper 95%**
1	Speed	4.827	0.184	0.000	**124.887**	87.015	179.242
2	Speed	4.427	0.173	0.000	**83.692**	59.642	117.442
3	Speed	4.383	0.187	0.000	**80.063**	55.514	115.470
4	Speed	1.878	0,197	0.000	**6.474**	4.402	9.521
6	Speed	4.247	0.190	0.000	**69.892**	48.137	101.479
7	Speed	-1.055	0.256	0.000	**0.348**	0.211	0.575
8 and 9	Speed	-1.382	0.274	0.000	**0.251**	0.147	0.430

Table 4.19 (a). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Internal/External Rotation Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-2.701	1.171	0.021	**0.067**	0.007	0.666
	Speed	6.038	0.383	0.000	**418.902**	197.943	886.516
	Injury	-1.101	0.827	0.132	0.287	0.057	1.453
	Interaction	-1.110	2.590	0.668	0.330	0.002	52.826
2	Intercept	-1.877	0.616	0.002	**0.153**	0.046	0.512
	Speed	4.978	0.381	0.000	**145.184**	68.830	306.240
	Injury	0.478	0.393	0.224	1.612	0.747	3.483
	Interaction	-1.807	2.467	0.464	0.164	0.001	20.656
3	Intercept	-1.377	116.058	0.991	0.252	0.000	>100,000
	Speed	3.640	0.413	0.000	**38.085**	16.967	85.487
	Injury	-5.165	8.178	0.528	0.006	0.000	52,212.266
	Interaction	-1.300	19.284	0.946	0.273	0.000	>100,000
4	Intercept	-1.234	0.625	0.048	**0.291**	0.086	0.991
	Speed	2.493	0.405	0.000	**12.102**	5.468	26.783
	Injury	0.618	0.409	0.130	1.856	0.833	4.136
	Interaction	-1.500	2.536	0.554	0.223	0.002	32.116
6	Intercept	-9.003	1.060	0.000	**0.000**	0.000	0.000
	Speed	0.213	2.621	0.935	1.237	0.007	210.548
	Injury	-1.173	1.642	0.475	0.309	0.012	7.724
	Interaction	0.686	8.226	0.934	1.986	0.000	>100,000
7	Intercept	-2.769	0.427	0.000	**0.063**	0.027	0.145
	Speed	-12.055	29.895	0.687	0.000	0.000	>100,000
	Injury	2.439	0.340	0.000	**11.458**	5.882	22.322
	Interaction	18.964	29.976	0.527	>100,000	0.000	>100,000
8	Intercept	-3.207	11.925	0.788	0.041	0.000	>100,000
	Speed	-39.444	0.000	-	0.000	-	-
	Injury	-4.406	5.916	0.456	0.012	0.000	1323.891
	Interaction	-1.995	0.000	-	0.136	-	-
9	Intercept	-16.323	1.990	0.000	**0.000**	0.000	0.000
	Speed	-0.720	2.933	0.806	0.487	0.002	152.736
	Injury	-1.132	3.203	0.724	0.322	0.001	171.784
	Interaction	0.018	0.000	-	1.018	-	-

Table 4.19(b). Mixed Effects Multinomial Logistic Regression Analysis for Glenohumeral Internal/External Rotation Kinematic EVA: Analysis for Speed, Injury and Interaction between Speed and Injury, with cells 8 and 9 combined. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-1.753	0.191	0.000	**0.173**	0.119	0.252
	Speed	4.492	0.181	0.000	**89.298**	62.664	127.254
	Injury	1.190	0.172	0.000	**3.286**	2.348	4.599
	Interaction	-1.979	0.578	0.001	**0.138**	0.044	0.429
2	Intercept	-0.105	0.169	0.533	0.900	0.647	1.253
	Speed	3.897	0.169	0.000	**49.251**	35.343	68.634
	Injury	0.588	0.133	0.000	**1.801**	1.387	2.339
	Interaction	-1.902	0.502	0.000	**0.149**	0.056	0.399
3	Intercept	-1.234	0.197	0.000	**0.291**	0.198	0.429
	Speed	3.968	0.199	0.000	**52.867**	35.762	78.154
	Injury	-0.931	0.246	0.000	**0.394**	0.243	0.638
	Interaction	-1.983	0.544	0.000	**0.138**	0.047	0.400
4	Intercept	-1.808	0.201	0.000	**0.165**	0.110	0.243
	Speed	1.414	0.199	0.000	**4.114**	2.786	6.076
	Injury	1.497	0.140	0.000	**4.466**	3.396	5.874
	Interaction	0.795	0.583	0.173	2.215	2.215	6.945
6	Intercept	-4.29	0.234	0.000	**0.014**	0.014	0.0217
	Speed	3.027	0.230	0.000	**20.641**	20.641	32.406
	Injury	0.539	0.160	0.001	**1.715**	1.715	2.348
	Interaction	-1.909	0.000	--	0.148	--	--
7	Intercept	-4.352	0.203	0.000	**0.129**	0.009	0.019
	Speed	-15.392	20.723	0.458	0.000	0.000	>100,000
	Injury	2.892	0.144	0.000	**17.328**	13.058	22.993
	Interaction	16.364	20.737	0.430	>100.000	0.000	>100,000
8 and 9	Intercept	-8.196	0.311	0.000	**0.000**	0.000	0.001
	Speed	-5.241	0.343	0.000	**0.005**	0.003	0.010
	Injury	1.229	0.144	0.000	**3.417**	2.579	4.53
	Interaction	9.219	1.067	0.000	**10083.731**	1245.294	81652.737

Table 4.20. Mixed Effects Multinomial Logistic Regression Analysis for Upper Trapezius EMG EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Speed	1.496	0.241	0.000	**4.465**	2.783	7.166
2	Speed	1.286	0.227	0.000	**3.619**	2.321	5.643
3	Speed	1.530	0.235	0.000	**4.616**	2.915	7.309
4	Speed	0.554	0.318	0.082	1.740	0.933	3.244
6	Speed	1.765	0.250	0.000	**5.842**	3.577	9.542
7	Speed	-1.658	0.740	0.027	**0.191**	0.044	0.825
8	Speed	-36.949	0.000	0.001	0.000	0.000	Infinity
9	Speed	0.313	0.290	0.280	1.368	0.775	2.414

Table 4.21. Mixed Effects Multinomial Logistic Regression Analysis for Upper Trapezius EMG EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	0.025	0.196	0.899	1.025	0.699	1.504
	Speed	1.814	0.311	0.000	**6.137**	3.339	11.279
	Injury	0.865	0.302	0.042	**2.375**	1.313	4.294
	Interaction	-0.875	0.499	0.079	0.417	0.157	1.108
2	Intercept	1.074	0.168	0.000	**2.928**	2.105	4.073
	Speed	1.475	0.287	0.000	**4.373**	2.491	7.675
	Injury	0.435	0.277	0.116	1.545	0.898	2.657
	Interaction	-0.582	0.471	0.216	0.559	0.222	1.406
3	Intercept	0.766	0.189	0.000	**2.150**	1.485	3.114
	Speed	1.762	0.298	0.000	**5.826**	3.252	10.438
	Injury	0.354	0.303	0.243	1.425	0.787	2.580
	Interaction	-0.685	0.485	0.158	0.504	0.195	1.305
4	Intercept	-0.861	0.290	0.003	**0.423**	0.240	0.746
	Speed	0.549	0.407	0.178	1.732	0.780	3.846
	Injury	0.294	0.395	0.457	1.341	0.619	2.907
	Interaction	-0.060	0.657	0.928	0.942	0.260	3.412
6	Intercept	0.028	0.242	0.909	1.028	0.640	1.652
	Speed	2.161	0.318	0.000	**8.682**	4.657	16.186
	Injury	0.278	0.350	0.427	1.320	0.665	2.619
	Interaction	-1.038	0.514	0.043	**0.354**	0.129	0.970
7	Intercept	-2.328	0.428	0.000	**0.098**	0.042	0.225
	Speed	-2.260	1.350	0.094	0.104	0.007	1.470
	Injury	0.879	0.489	0.072	2.409	0.924	6.278
	Interaction	0.685	1.631	0.675	1.983	0.081	48.456
8	Intercept	-2.121	0.461	0.000	**0.120**	0.049	0.296
	Speed	-37.140	0.000	-	0.000	0.000	-
	Injury	-0.733	0.882	0.406	0.480	0.085	2.705
	Interaction	-0.549	0.000	-	0.578	0.000	-
9	Intercept	-0.825	0.322	0.010	**0.438**	0.233	0.823
	Speed	1.348	0.338	0.001	**3.849**	1.984	7.470
	Injury	0.554	0.392	0.157	1.741	0.808	3.750
	Interaction	-2.996	0.590	0.000	**0.050**	0.016	0.159

Table 4.22. Mixed Effects Multinomial Logistic Regression Analysis for Serratus Anterior EMG EVA: analysis for speed only. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	**Effect**	**Estimate**	**Standard Error**	**p-Value**	**Odds Ratio**	**Lower 5%**	**Upper 95%**
1	Speed	2.394	0.321	0.000	**10.960**	5.841	20.566
2	Speed	2.401	0.307	0.000	**11.039**	6.047	20.150
3	Speed	3.258	0.316	0.000	**25.991**	13.988	48.293
4	Speed	0.123	0.455	0.787	1.131	0.464	2.578
6	Speed	3.487	0.326	0.000	**32.687**	17.256	61.917
7	Speed	-4.245	2.347	0.071	0.014	0.000	1.428
8	Speed	-36.073	0.000	0.000	0.000	-	-
9	Speed	2.945	0.353	0.000	**19.011**	9.514	37.987

Table 4.23. Mixed Effects Multinomial Logistic Regression Analysis for Serratus Anterior EMG EVA: Analysis for Speed, Injury and Interaction between Speed and Injury. All cells are referenced to cell 5. Statistically significant odds ratios are presented in bold type. Lower and upper confidence limits are presented for the lower and upper 5th percentiles. Odds ratios below 1 indicate a decreased likelihood of the data point being in the considered cell compared to being in the reference cell (cell 5), and an odds ratio greater than 1 indicates an increased likelihood of being in the considered cell compared to the reference cell.

EVA Cell	Effect	Estimate	Standard Error	p-Value	Odds Ratio	Lower 5%	Upper 95%
1	Intercept	-0.252	0.184	0.171	0.777	0.542	1.115
	Speed	2.459	0.409	0.000	**11.690**	5.241	26.074
	Injury	0.487	0.270	0.072	1.628	0.958	2.765
	Interaction	-0.062	0.660	0.925	0.940	0.258	3.424
2	Intercept	0.678	0.152	0.000	**1.990**	1.479	2.677
	Speed	2.370	0.387	0.000	**10.698**	5.016	22.816
	Injury	0.253	0.236	0.284	1.288	0.810	2.048
	Interaction	0.122	0.634	0.847	1.130	0.326	3.913
3	Intercept	0.055	0.176	0.754	1.057	0.748	1.492
	Speed	3.218	0.398	0.000	**24.987**	11.454	54.507
	Injury	0.223	0.279	0.424	1.250	0.724	2.161
	Interaction	0.131	0.651	0.841	1.140	0.318	4.081
4	Intercept	-1.072	0.247	0.000	**0.342**	0.211	0.555
	Speed	-0.112	0.597	0.852	0.895	0.278	2.881
	Injury	0.044	0.335	0.895	1.045	0.542	2.015
	Interaction	0.627	0.917	0.494	1.873	0.310	11.300
6	Intercept	-0.857	0.223	0.000	**0.424**	0.274	0.657
	Speed	3.470	0.414	0.000	**32.142**	14.289	72.301
	Injury	0.899	0.306	0.003	**2.457**	1.348	4.478
	Interaction	0.082	0.667	0.902	1.086	0.294	4.016
7	Intercept	-1.063	0.275	0.000	**0.346**	0.201	0.593
	Speed	-13.841	303.711	0.964	0.000	0.000	>100,000
	Injury	-0.603	0.376	0.108	0.547	0.262	1.143
	Interaction	11.355	303.721	0.970	85,375.647	0.000	>100,1000
8	Intercept	-2.144	0.380	0.000	**0.117**	0.056	0.247
	Speed	-36.519	0.000	-	0.000	-	-
	Injury	-0.546	0.663	0.410	0.579	0.158	2.124
	Interaction	-0.574	0.000	-	0.563	-	-
9	Intercept	-2.972	0.366	0.000	**0.051**	0.025	0.105
	Speed	2.966	0.447	0.000	**19.420**	80.95	46.592
	Injury	0.867	0.367	0.018	**2.379**	1.159	4.884
	Interaction	-0.108	0.728	0.882	0.897	0.215	3.740

Figure 4.1. Scapula Tilting Kinematic EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular scapular tilting amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.

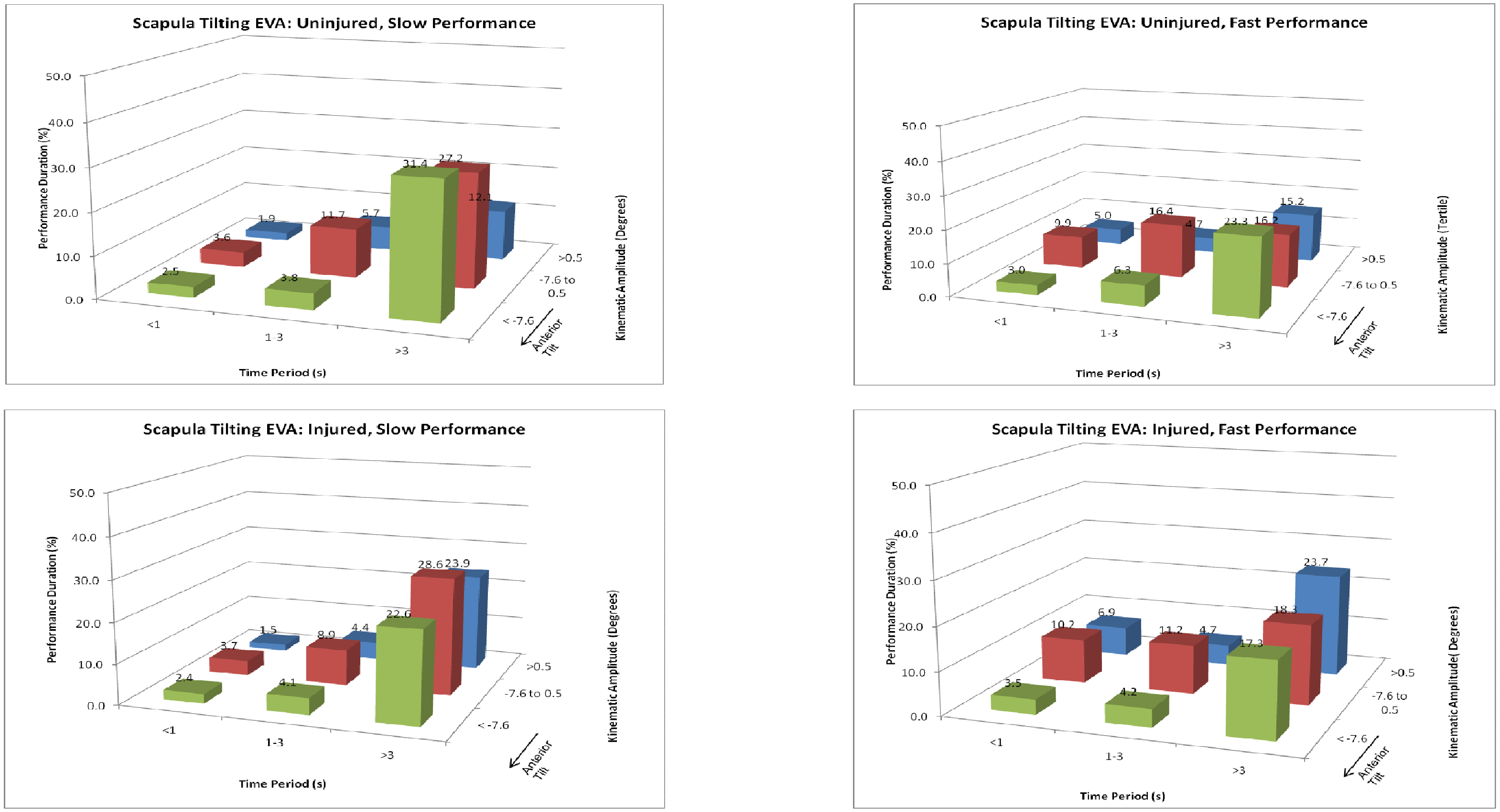


Figure 4.2. Scapula Upward Rotation Kinematic EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular scapular upward rotation amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.

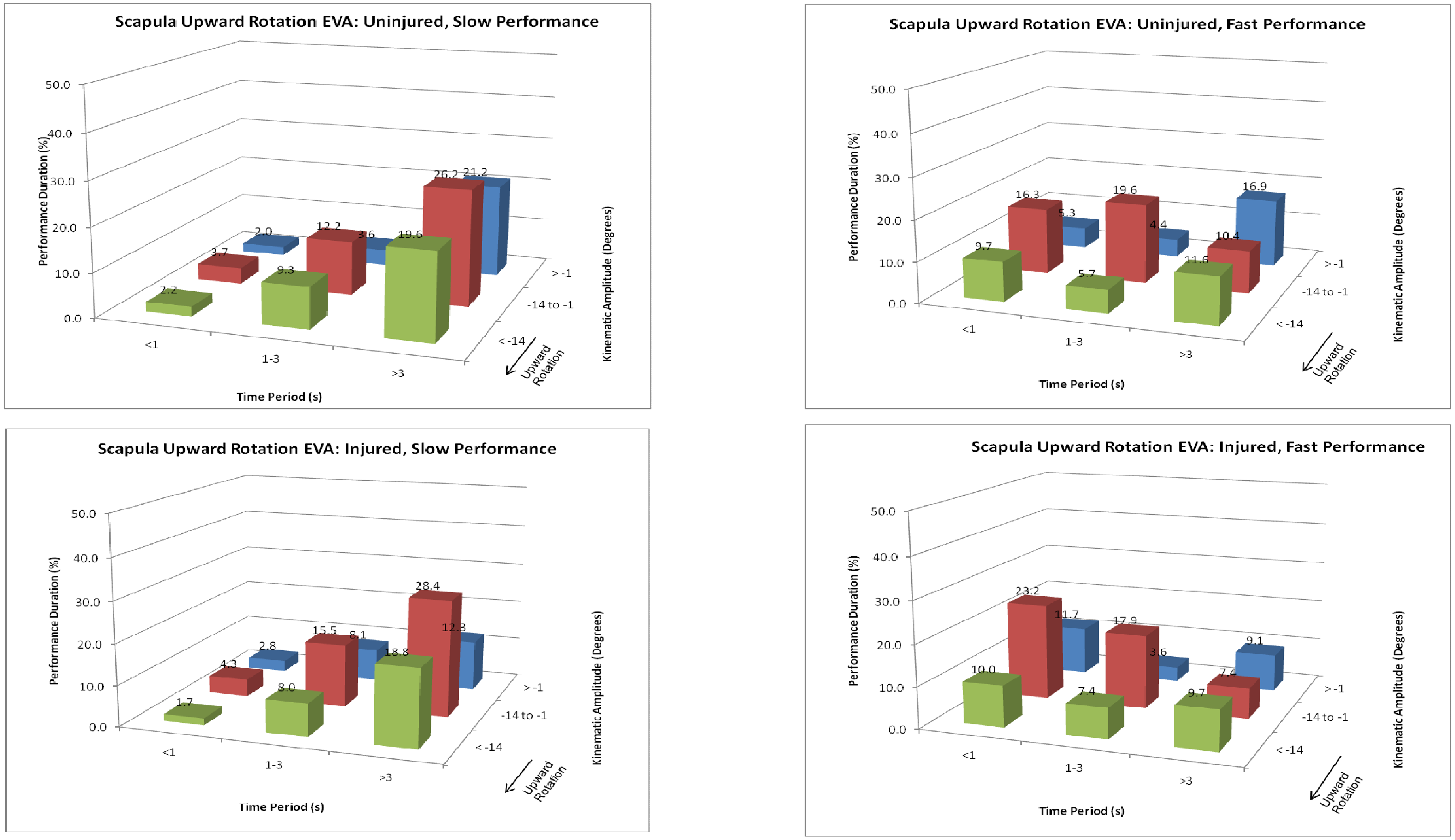
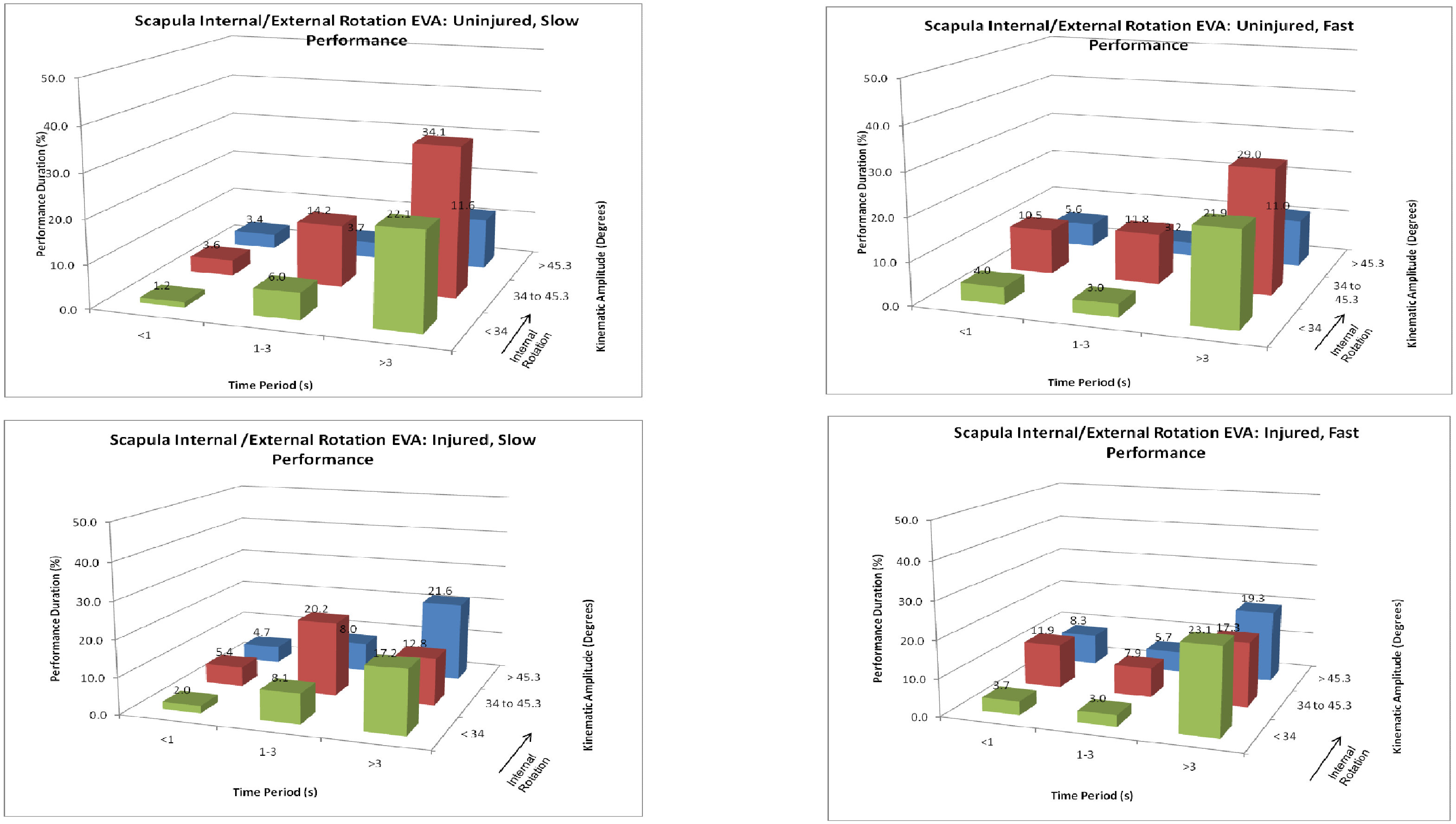


Figure 4.3. Scapula Internal/External Rotation Kinematic EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular scapular internal/external rotation amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.



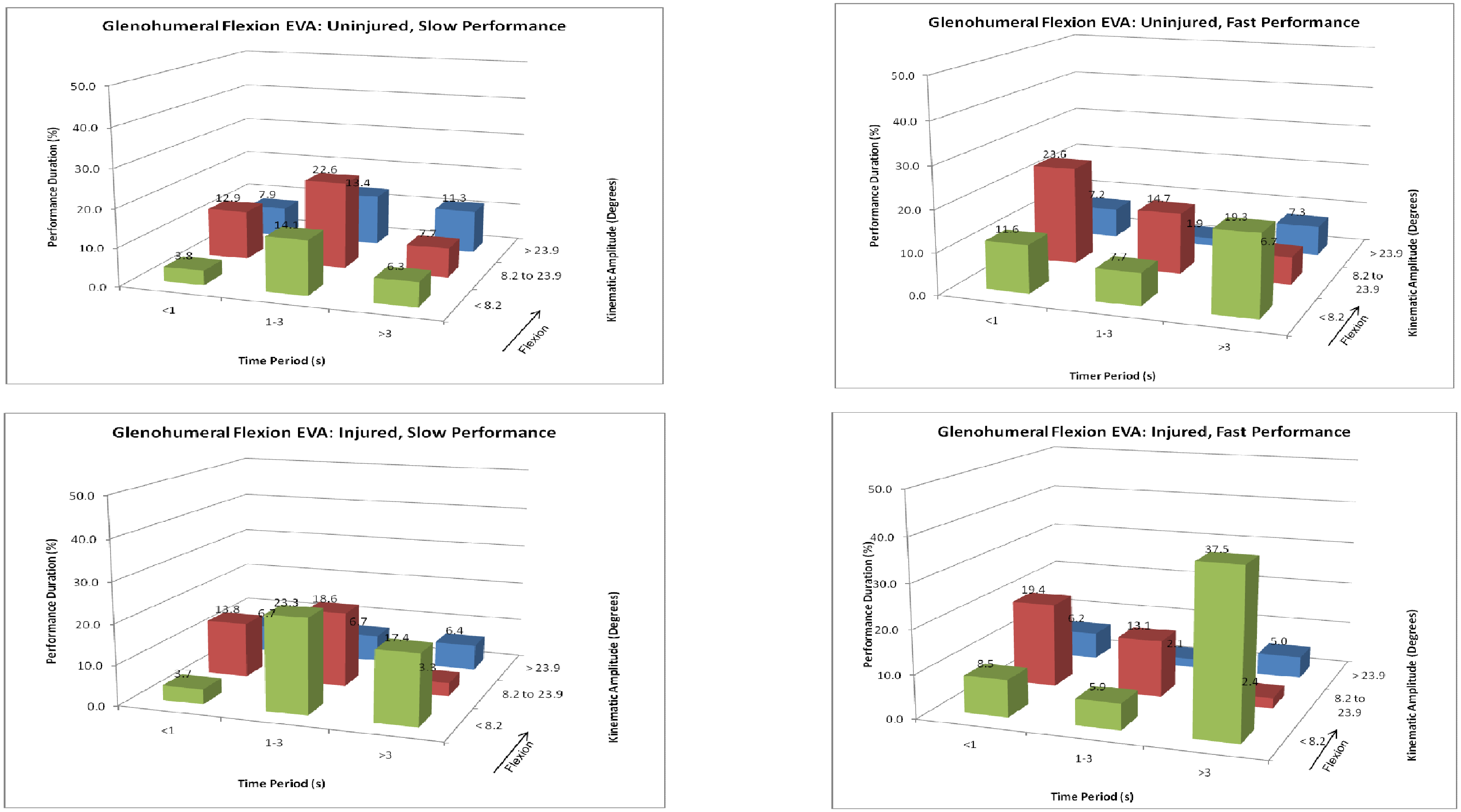
Scapula Internal/External Rotation EVA: Uninjured, Slow Performance

Scapula Internal/External Rotation EVA: Uninjured, Fast Performance

Scapula Internal /External Rotation EVA: Injured, Slow Performance

Scapula Internal/External Rotation EVA: Injured, Fast Performance

Figure 4.4. Glenohumeral Flexion Kinematic EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular glenohumeral flexion amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.



Glenohumeral Flexion EVA: Uninjured, Slow Performance

Glenohumeral Flexion EVA: Uninjured, Fast Performance

Glenohumeral Flexion EVA: Injured, Slow Performance

Glenohumeral Flexion EVA: Injured, Fast Performance

Figure 4.5 Glenohumeral Abduction Kinematic EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular glenohumeral abduction amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.

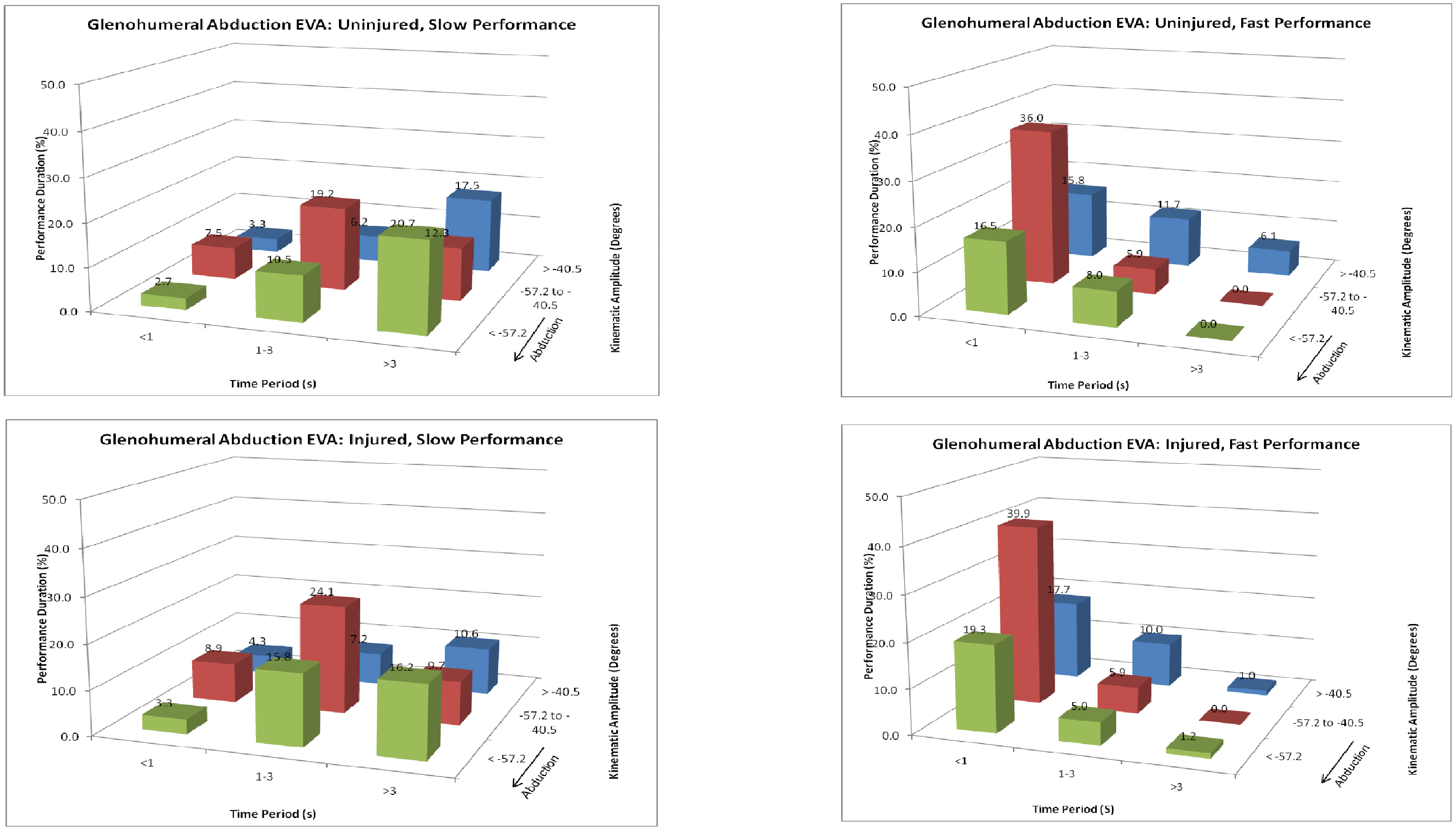


Figure 4.6. Glenohumeral Internal/External Rotation Kinematic EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular glenohumeral internal/external rotation amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.

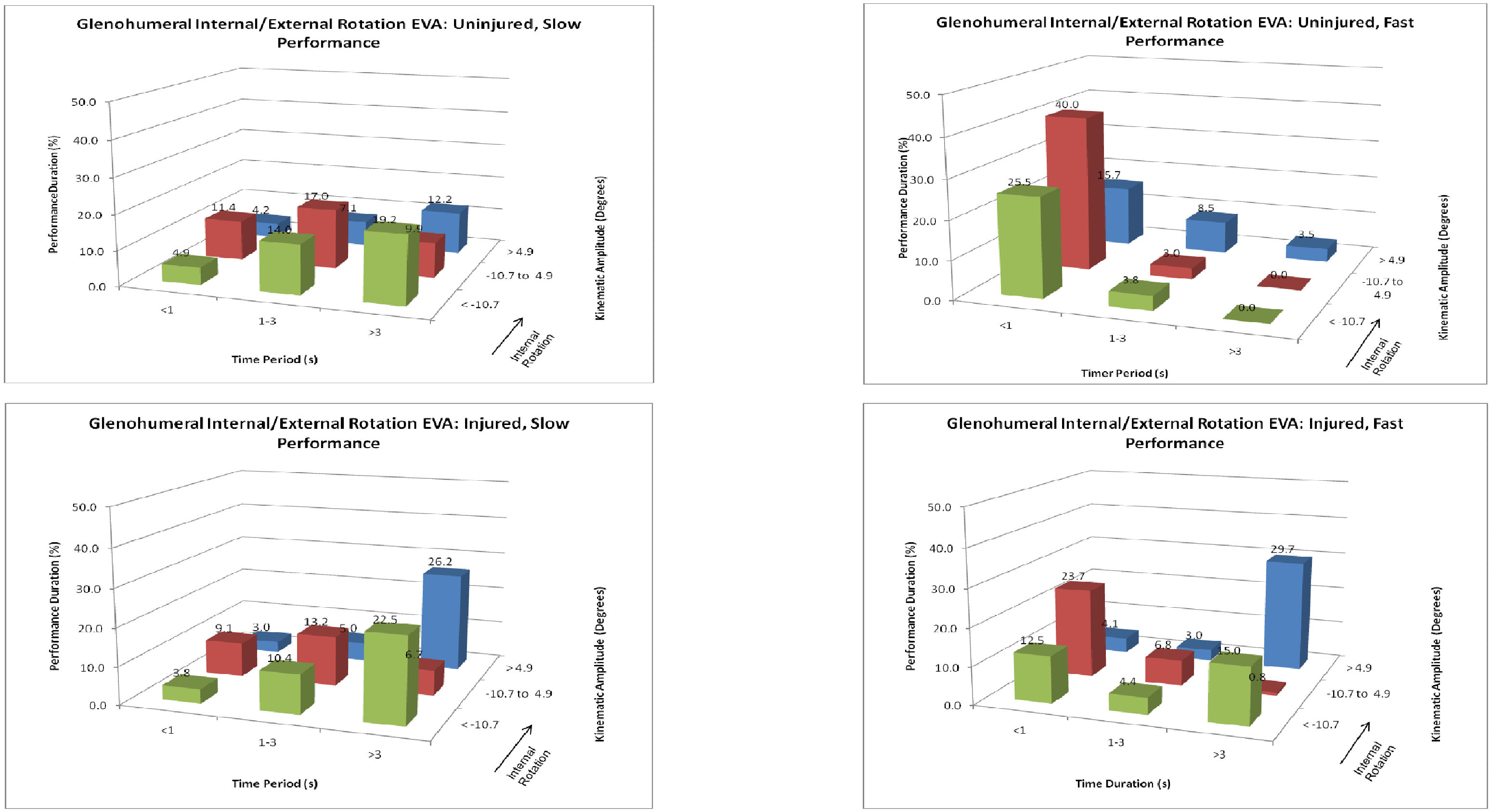


Figure 4.7 Upper Trapezius EMG EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular upper trapezius amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.

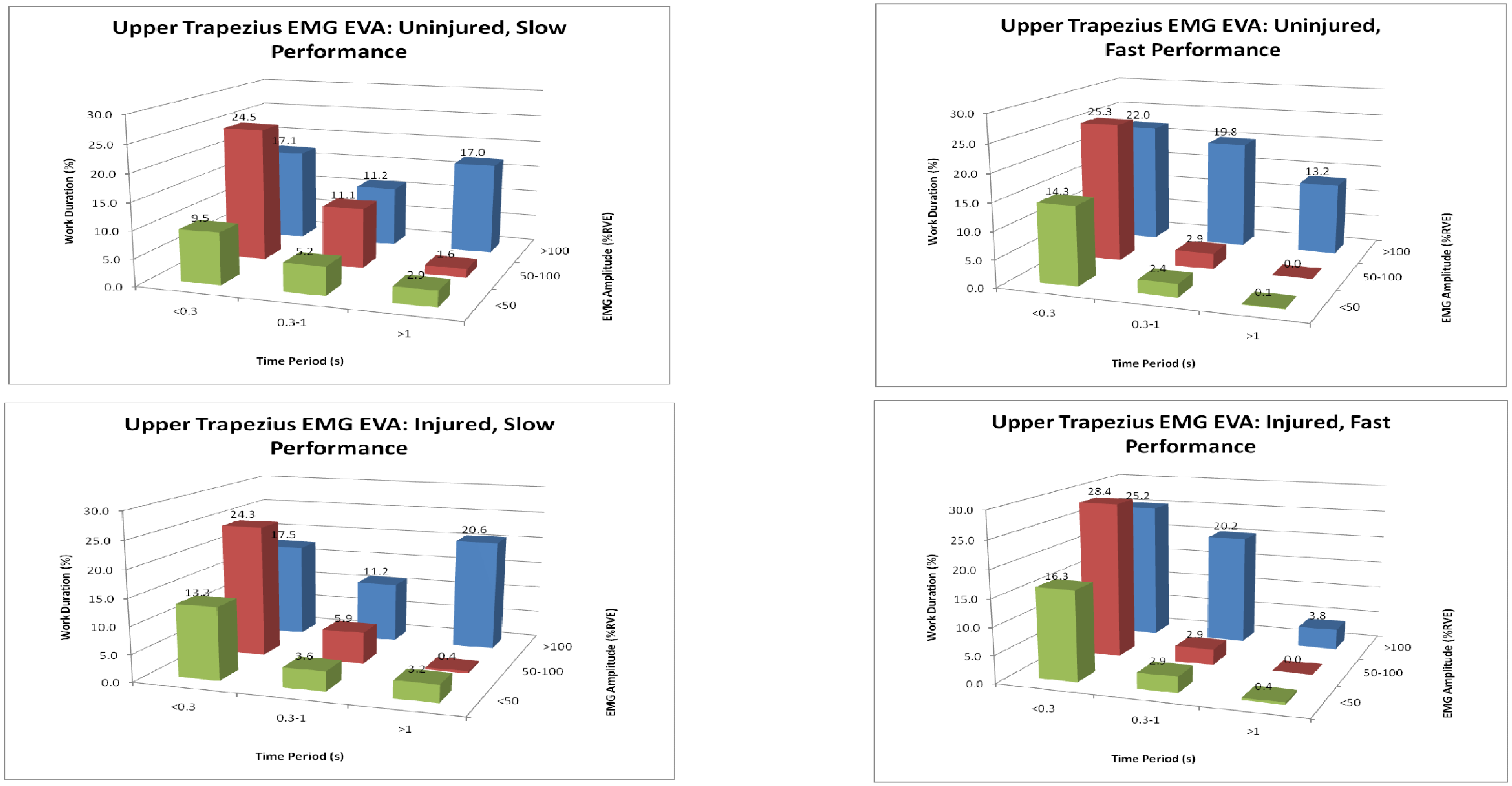


Figure 4.8. Serratus Anterior EMG EVA Graphs for Slow and Fast Performance and Uninjured and Injured Participants. Each graph represents the percentage of time spent (vertical, or y-axis) at a particular serratus anterior amplitude level (depth axis) for a particular duration of time in seconds (horizontal or x-axis). Speed differences are represented by left to right changes between graphs, and injury effects by top to bottom changes.

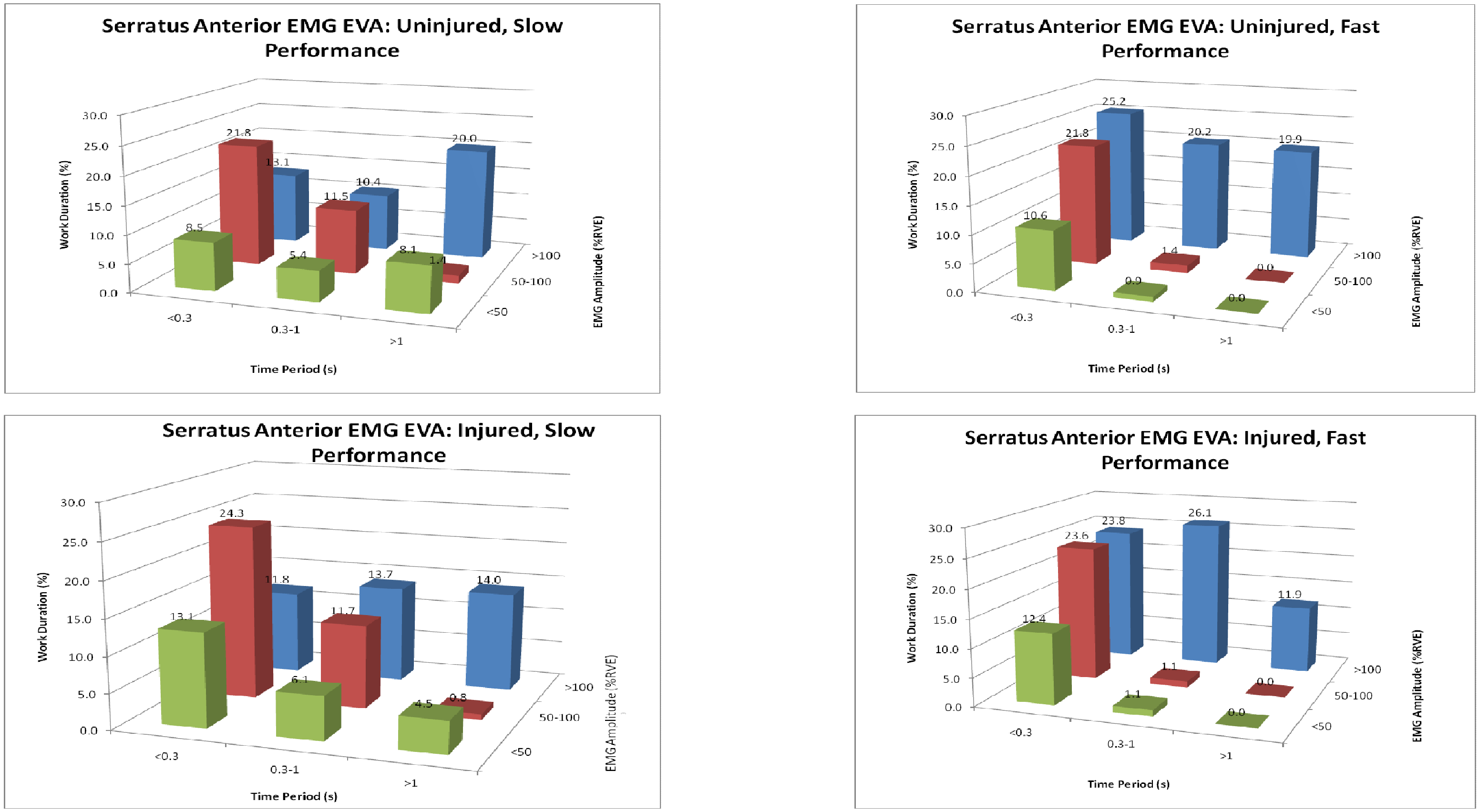


Table 4.24 Two-Way Analysis of Variance Analysis of Scapular Tilting during Arm Elevation between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	48	0.87	0.356
Speed	1	48	5.32	0.026*
Injury*Speed	1	48	0.56	0.459

* Significant at the level p ≤ 0.05

Table 4.25 Two-Way Analysis of Variance Analysis of Scapular Upward Rotation during Arm Elevation between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	48	0.04	0.841
Speed	1	48	1.65	0.205
Injury*Speed	1	48	0.03	0.871

* Significant at the level p ≤ 0.05

Table 4.26. Two-Way Analysis of Variance Analysis of Scapular Internal/External Rotation during Arm Elevation between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	48	0.41	0.525
Speed	1	48	4.68	0.036*
Injury*Speed	1	48	0.44	0.512

* Significant at the level p ≤ 0.05

Table 4.27. Two-Way Analysis of Variance Analysis of Glenohumeral Flexion during Arm Elevation between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	48	3.58	0.064
Speed	1	48	49.54	<0.001*
Injury*Speed	1	48	1.17	0.284

* Significant at the level $p \leq 0.05$

Table 4.28 Two-Way Analysis of Variance Analysis of Glenohumeral Abduction during Arm Elevation between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	48	0.10	0.759
Speed	1	48	1.35	0.251
Injury*Speed	1	48	0.12	0.732

* Significant at the level $p \leq 0.05$

Table 4.29 Two-Way Analysis of Variance Analysis of Glenohumeral Internal/External Rotation during Arm Elevation between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	48	0.38	0.542
Speed	1	48	2.78	0.102
Injury*Speed	1	48	0.62	0.435

* Significant at the level $p \leq 0.05$

Table 4.30 Two-Way Analysis of Variance Analysis of Upper Trapezius EMG between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	48	1.71	0.197
Speed	1	48	11.26	0.002*
Injury*Speed	1	48	4.63	0.036*
Contrast – Slow	1	48	1.71	0.197
Contrast – Fast	1	48	0.27	0.606

* Significant at the level p ≤ 0.05

Table 4.31 Two-Way Analysis of Variance Analysis of Serratus Anterior EMG between 50 and 65 Degrees for Injury, Speed, and the interaction between Injury and Speed.

Source	**NDF**	**DDF**	**F-value**	**p-value**
Injury	1	47	0.00	0.911
Speed	1	47	23.95	<0.001*
Injury*Speed	1	47	0.86	0.302

* Significant at the level p ≤ 0.05

Table 4.32. Scapula resting posture for injured and uninjured groups. Data are presented as means, with confidence limits, and Student's t-tests with p-values for all three scapula rotations.

Scapula Posture Variable		**Lower Confidence Limit**	**Mean**	**Upper Confidence Limit**	**t-value**	**p-value**
Tilting	Uninjured	-15.04	-12.75	-10.46	0.12	0.906
	Injured	-16.82	-12.99	-9.17		
Internal/External Rotation	Uninjured	34.38	36.72	39.06	-0.57	0.571
	Injured	33.76	37.94	42.11		
Upward Rotation	Uninjured	1.43	4.10	6.77	0.26	0.798
	Injured	-0.29	3.54	7.37		

Table 4.33. Intraclass Correlation Coefficients [2,1] (ICC) of dependent variables for all data analyzed separately by speed at 5 seconds, 15 seconds and 25 seconds of the musical performance over 50ms time windows.

	5 Seconds		**15 Seconds**		**25 Seconds**	
Dependent Variable	**Slow**	**Fast**	**Slow**	**Fast**	**Slow**	**Fast**
Scapula Tilting	0.95	0.95	0.98	0.94	0.95	0.94
Scapula Upward Rotation	0.93	0.90	0.97	0.87	0.94	0.88
Scapula Int./Ext. Rotation	0.91	0.94	0.95	0.94	0.94	0.93
GHJ Flexion	0.73	0.91	0.92	0.86	0.85	0.86
GHJ Abduction	0.88	0.64	0.94	0.68	0.89	0.59
GHJ Int./Ext. Rotation	0.95	0.92	0.99	0.88	0.96	0.90
Upper Trapezius	0.63	0.59	0.54	0.47	0.51	0.48
Serratus Anterior	0.55	0.63	0.54	0.54	0.65	0.60

CHAPTER 5

DISCUSSION

Current Study in the Context of Previous Relevant Studies

Despite the fact that several questionnaire studies have indicated that shoulder injuries are relatively common in violinists, few scientifically sound investigations were found that have investigated injuries in the musician population. Those studies that have attempted to investigate shoulder injuries in violinists fall into two groups: those implementing EMG methods of analysis (Berque and Gray, 2002; Philipson et al, 1990; Levy et al, 1992) and those employing kinematic analysis (Tulchinsky and Riolo, 1994; Turner Stokes and Reid, 1999; Shan and Visentin, 2003; Shan et al, 2004). The *a priori* difference between previous studies and the current one is that the current study utilizes both kinematic and EMG methods of analysis in an effort to determine factors that may be associated with subacromial impingement in violin musicians.

Summary of Previous Kinematic Analysis Studies in Violinists

Among those studies that used kinematic analysis, Tulchinsky and Riolo (1994) used a two-dimensional camera technique utilizing one camera and reflective skin markers to track the motion of the bow arm (right arm) in 9 uninjured female professional violinists. Slow camera shutter speed, in addition to the use of only one camera, limited the utility of the technique from a kinematic point of view, since motion was not described in clinically relevant anatomical terms. The researchers used these methods to describe bow arm motions and reported elbow flexion and extension angles, as well as vertical heights of the lateral epicondyle and acromion relative to one-another in a vertical plane. They studied only 9 women, and this was a qualitative study, that would be open to subjective interpretation, including the projection angle errors of single camera filming. No actual description of shoulder motion was made, other than the position of the elbow relative to the acromion. The current study used three-dimensional (3-D) kinematic methods, utilizing embedded local coordinate systems (LCD) to track shoulder bony segment rotations about orthogonal axes to describe 3-D motion. These methods are less prone to projection angle error than those used by Tulchinsky and Riolo (1994).

In an attempt to determine possible causes of shoulder impingement in violinists, Turner Stokes and Reid (1999) tested 39 uninjured string players to determine shoulder and elbow motion in violin, viola and cello musicians: 20 violinists were tested. They used a two-camera technique and were limited in the expression of shoulder motion to three-dimensional terms, resulting in motion being expressed in only one plane and making clinical relevance questionable, particularly since the plane was not mentioned. Despite reporting this as a three-dimensional study, they cite difficulties in interpreting their results and concede that they are really two-dimensional. They claim to have reproducibly defined motion of the bow arm in these musicians to be used to determine possible motion artifacts that may cause musculoskeletal pathology. These methods are prone to projection angle error which the current study sought to eliminate in the use of Cardan and Euler angle rotations about embedded LCS. The present study was able to discern differences in scapula and glenohumeral rotation about 3 orthogonal axes to explain the motion strategies adopted by violinists with SIS, and these methods are recommended in an effort to describe the kinematics of the shoulder (van der Helm, 2001).

Shan and Visentin (2003) tested 8 professional violinists and three students performing standardized musical repertoire. They used nine synchronized cameras to measure three-dimensional arm motion in violinists. They expressed arm motions relative to cardinal planes during performance of musical repertoire, and related these to the string being played on. However, they were not able to describe motion between bony segments, particularly in the shoulder, where scapulothoracic motion can be a significant contributor to shoulder pathology. They did not mathematically embed a local coordinate system (LCS) into each shoulder segment. As a result, they were prevented from extracting an adequate three dimensional measurement of inter-segmental scapulothoracic or glenohumeral displacement along, or rotation about, three respective orthogonal axes, that in the present study were aligned with clinically relevant axes that emanate perpendicularly from three anatomical planes of motion, namely the sagittal, coronal and transverse planes. Consequently, this lack of data limited their identification of the mechanics associated with SIS, since it has been shown that SIS is associated with scapula and glenohumeral motion, for example scapula downward rotation and reduced posterior tilting during glenohumeral elevation in the scapula plane (Ludewig and Cook, 2000).

Researchers have typically used peak measurements of range of motion to comment on motions that apparently pose risks to the musician (Shan and Visentin, 2003), rather than observing the relative period of time spent at various ranges of motion, as may have been possible with an exposure variation analysis (EVA) (Mathiassen and Winkel, 1991). Performers in Shan and Visentin’s study (Shan and Visentin, 2003) may have briefly moved the joint in question to a particular extreme point in the range, yet may have spent a majority of the performance time at more comfortable or acceptable ranges than the extreme. This may tend to misrepresent the exposure of the joint to awkward posture. The current study utilized the data reduction technique known as exposure variation analysis (EVA) which affords simultaneous analysis of amplitude and time period (frequency) spent at various amplitude levels.

Summary of Previous EMG Analysis Studies in Violinists

Philipson et al (1990) used surface EMG analysis on upper trapezius, deltoid, biceps, and triceps muscles of 9 “injured” professional violinists during the performance of standardized repertoire comparing mean EMG to that of uninjured counterparts. They found that the injured musicians played with greater mean upper trapezius EMG than the uninjured musicians. It is not known what injury the injured group had. The use of mean EMG is problematic, since it does not give any detail of the frequency of activation, which has been shown to impact incidence of injury (Veiersted et al, 1993). Therefore the signal that they obtained did not necessarily reveal any useful information about the relative muscle exposure in the musical performance, since mean EMG may be elevated by brief periods of high or low EMG, which may have little clinical relevance because of actual time spent at such levels. Conversely, the EMG signal may have remained relatively constant for the duration of the performance, yielding the same result for what may have been a completely different recruitment pattern.

Berque and Gray (2002) used a similar method of recording average EMG in injured and uninjured groups of violinists using a more sophisticated EMG normalization technique and a more reliable EMG electrode placement technique as described by Mathiassen et al (1995). Pain-free subjects recorded higher mean upper trapezius activity (9% RVE difference) than musicians with neck and shoulder pain (p=0.05). However, the authors summed the left and right upper trapezius %RVE in this test, thereby failing to discern side-to-side differences, or the impact of side-specific effects. Violin performance is an asymmetrical activity, and the activity of one extremity may off-set that of the other since muscle groups are not performing the same types of activity in the two extremities. They acknowledged that there were insignificant differences in the recruitment of these two muscle groups (p=0.265), but failed to note differences between the groups (injured and uninjured) with “side” as a co-factor. Their sample size was also small: 4 males and 6 females. The current study investigated muscular activity on one side only in an effort to understand the relationship of such muscle activity to violin performance in injured and uninjured performers.

Berque and Gray (2002), and Philipson et al (1990) used average EMG as the dependent variable in upper extremity EMG studies in string players. Musicians interpret the same repertoire differently and express their interpretation of the music with dynamic movements in their upper extremities. Therefore the average EMG across subjects may not be truly representative of the exposure of the musicians to muscle use.

Summary of Current Study

The use of both EMG and kinematic exposure variation analysis (EVA) methods was found to be useful in reliably assessing factors associated with subacromial impingement syndrome (SIS) in violinists. Intraclass correlation coefficients (ICC) indicated that the EVA method was repeatable. The EVA method was also able to discern differences in terms of speed in both injured and uninjured participants. Injured musicians were noted to play in positions characterized by increased posterior scapular tilting for longer durations of time, increased scapular upward rotation for longer durations of time, and increased scapular internal rotation at slow speeds. Injured musicians were also noted to adopt positions of increased scapular posterior tilting, increased scapular upward rotation for longer durations of time, and increased internal rotation at fast speeds. When compared to their uninjured counterparts, injured musicians were also noted to perform with reduced amplitude but more static (longer duration) glenohumeral flexion, as well as with increased external rotation. Lastly, injured musicians were noted to perform with increased short duration, low amplitude upper trapezius activity at slow speeds, while they played with reduced long duration, high amplitude recruitment at fast speeds; these findings indicate that they recruited their upper trapezius less than was anticipated, since increased upper trapezius has been found to be associated with SIS in other populations (Ludewig and Cook, 2000). Lastly, injured musicians were noted to demonstrate increased amplitude of recruitment of serratus anterior at both slow and fast speeds. Serratus anterior amplitude has been previously found to be more associated with lower incidence of SIS rather than higher levels of recruitment in injured subjects.

The EVA method of data reduction employed in this study was instrumental in identifying these differences where more traditional methods failed to identify group differences. This study has therefore identified a reliable kinematic and EMG data reduction technique that can be used to assess the kinematics of shoulder motion as well as the upper trapezius and serratus anterior muscle activation in violin musicians.

Three-dimensional kinematic analysis was used in the present study to determine factors that may be associated with subacromial impingement syndrome (SIS). Local coordinate systems were mathematically embedded into shoulder bony structures and individual segment rotations were expressed using Euler/Cardan angle methods recommended by the International Society for Biomechanics (van der Helm, 2001). Motions were expressed in terms that have clinical relevance to medically trained professionals, since they were described in reference to anatomical planes.

Furthermore, this study used EVA data reduction methods first described by Mathiassen and Winkel (1991), rather than relying on temporal analysis of EMG amplitude or joint rotational excursion. These methods afforded the simultaneous assessment of amplitude variability (EMG or kinematic amplitude) and time spent at a particular level of amplitude. No studies have been performed on violinists using well established Euler/Cardan angle methodology based on embedded local coordinate systems (LCS), and none has used the EVA data reduction technique to assess motion or myoelectric activity to assess factors associated with injury.

Observations and Conclusions Relating to Demographic Data

The majority of the participants in the study were female (n=36). Despite the fact that males outnumber females in professional orchestras (Fishbein et al, 1988), females report and present with more injuries than their male counterparts (Fishbein et al, 1988, Hartsell and Tata, 1991; Cayea and Manchester, 1998; Dawson, 1988; Fry, 1987). The incidence of injury in this study matched the reported incidence rate (2:1) from previous research (Fishbein et al, 1988, Cayea and Manchester, 1998).

The results suggest that older musicians have a greater tendency to develop subacromial impingement syndrome (SIS) with injured subjects having an average age of 46.8 (± 3.5) years and uninjured participants an average age of 37.1 (± 3.0) years ($p=0.044$). Fishbein et al (1988) reported that the average age of professional male musicians is 43 and females is 40, however, they did not comment on the incidence of injury by age. Other studies that have investigated the incidence of musculoskeletal injuries in musicians (Hartsell and Tata, 1991; Cayea and Manchester, 1998; Dawson, 1988; Fry, 1987) focused on student populations, and their analyses are therefore impossible to relate to older or professional musicians. Fry (1986) reported a higher incidence of injury in Australian orchestra musicians between the ages of 26-30 than any other age group, with a steady decline with increasing age up to age 50. After age 50, the incidence remains the same up to age 70, after which it drops markedly again, as would be expected. The incidence in the 19-25 age grouping is about the same as it is for the 36 to 45 age group.

Professional musicians are more likely to seek care for such injuries than amateurs, since their livelihood depends on their ability to play. Amateur musicians are usually otherwise employed, and the urgency to seek care may not be as evident. Alternatively, professional musicians are more likely to have a higher relative exposure to violin performance, whereas their amateur colleagues have a more mixed exposure, with other activities being included in their day-to-day activities. However, this is not borne out in the data regarding their practice and performance time, since no significant differences were noted in terms of these factors (Table H1, Appendix H). The suggestion in the data that more professional musicians have SIS may therefore be an erroneous assumption.

It is also possible that amateur and student musicians are more apt to participate in a study such as this, which required about 90 to 120 minutes total laboratory time to complete. The uninjured population of this study was recruited with apparent ease and was made up of 25 amateurs and students. The $20 paid to participants would probably have been more enticing to students than to the non-student population, particularly the professional musicians. The injured participants took much longer to recruit, and it is likely that those professional musicians who decided to participate were more likely to do so if they had an injury than if they were participating merely to contribute for other reasons. The median hourly income for professional musicians in the United States of America (USA) is $19.73 and in Minnesota is $21.74 (Bureau of Labor Statistics, US Department of Labor). The rate for the top 10% (earning capacity only) of professional musicians in the USA is $57.37 and in Minnesota exceeds $70.00 (Bureau of Labor Statistics, US Department of Labor). The American Federation of Musicians reported that the weekly minimum salary in a major orchestra ranged from $700 to $ 800 per week during the 2004/5 season (Bureau of Labor Statistics, US Department of Labor). Public School music teachers can expect remuneration of $17,000 to $45,000 per annum, while college professors can expect $18,000 to $77,000 (National Association of Music Education). The minimum salary that professional musicians in the Minnesota Orchestra can expect to receive is $1,827 per month as of April 1st 2007, with additional amounts for overtime, special functions, or playing an instrument that is not listed as their primary instrument (Twin Cities Musicians Union, private correspondence). The base annual salary for the St. Paul Chamber Orchestra is listed as $71,585 for the 2008/9 season (Twin Cities Musicians Union, private correspondence). Amateur musicians can expect to receive $85.00 for the first two hours of work, and $10 for each additional hour (Twin Cities Musicians Union, private correspondence). It therefore seems likely that professional musicians would be less apt to participate in a study of this nature, unless they felt driven to do so in the interests of contributing to lessening injury incidence in their profession.

Observations and Conclusions Relating to Physical Examination

Physical examination results were mostly consistent with anticipated findings. Three participants were omitted since they presented with impingement yet reported no pain. Two of the three that were omitted for this reason also reported no pain on manual muscle testing. Therefore they did not clearly fit into either of the two groups and served to confound the group determination.

The angle of kyphosis in the standing position was appeared to be greater in the injured group, although no significant differences were noted between the two groups (p=0.350). These results conflict with those of Kebaetse et al (1999), who found that increased degrees of kyphosis were associated with SIS. It is possible that a larger sample would need to be evaluated to reach a level of significance. It is also possible that the method used in this study to measure kyphosis, which merely comprised measurement of minimum kyphosis in the erect standing posture, differed from that used by Kebaetse et al, who measured minimum kyphosis with the participant extending the thoracic spine as far as possible into extension.

Participants were grouped in this study according to the presence of pain within 2 weeks prior to data collection, their testing positive on at least 2 of 5 subacromial impingement tests, and the report of pain with manual muscle testing of the rotator cuff. Unsurprisingly, therefore, significant differences were noted in these factors between the two groups with respect to range of motion, pain on manual muscle testing, and impingement testing.

No differences in instrument dimensions were identified between the two groups. Mismatches between the musician and the size of the instrument have been cited as possible reasons for the musculoskeletal injuries seen in musicians (Blum and Ahlers, 1994). However, this is more likely to be evident in those that play larger instruments, such as the viola or double bass. Blum and Ahlers (1994) found that injury incidence in viola musicians was higher than in violin musicians, and this was attributed to the size difference between the two instruments. The bow weight was not measured for this study. Bows are typically very light and the *PinchTrack* instrument that was used to measure the violin weight would not have the desired resolution to accurately measure the weight of the bow.

Visually observed resting scapula posture was not found to be reliably consistent with resting posture measured kinematically. Burkhart et al (2003) emphasized the importance of observing and measuring the scapula orientation in clinical assessment and using this to determine the appropriate course of action in remedying scapulo-thoracic malalignment. While the importance of scapula posture is not disputed, a more reliable clinical test needs to be established to determine scapula resting posture.

Observations and Conclusions: Kinematic Data

It was anticipated that injured participants in this study, when compared to their non-injured counterparts, would perform with a more static performance style with respect to scapulothoracic (hypothesis 5) and glenohumeral (hypothesis 6) motion. This factor would be borne out in the presence of significant proportions of time spent in cells 7, 8 and 9 of the EVAs for kinematic and EMG variables. It was further posited that they would demonstrate tendencies to play in positions of decreased scapula upward rotation and increased anterior tilting (hypothesis 5), as well as increased glenohumeral internal rotation (hypothesis 6), or that they would employ a combination of these postures. It was also anticipated that they would adopt these postures for prolonged periods of time, rather than moving in and out of these postures with high frequency. These hypotheses were based on research that indicated that SIS was associated with apparently abnormal scapulothoracic motion (Lukasiewicz et al, 1999; Ludewig and Cook, 2000; Graichen et al, 2001; and Endo et al, 2001) who showed that that, with arm elevation, the scapula was noted to show decreased posterior scapular tilting and decreased scapular upward rotation than in uninjured persons.

Not all the scapulothoracic and glenohumeral trends that have been reported in previous studies as being associated with SIS were identified in this study. Ludewig and Cook (2000) found that reduced scapula upward rotation at 60^o glenohumeral elevation in the scapula plane was associated with SIS, as was increased anterior tilting of the scapula at 120^o glenohumeral elevation in the scapula plane. Endo et al (2001) and Su et al (2004) found similar results with respect to scapula downward rotation in those with confirmed impingement. Several researchers found that the scapula upwardly rotates on arm elevation (Deutsch et al, 1996; Paletta et al, 1997; Graichen et al, 2001; Yamaguchi et al, 2000; Mell et al, 2001) in those with full thickness tears in the rotator cuff. This result, however, may be confounded by projection angle error since these studies were performed using radiographic and magnetic resonance imaging rather than true 3-D methodology with local coordinate systems embedded into bony segments of the shoulder. More recent study by McClure et al (2006) confirmed these findings and showed that, using surface mounted sensors and the creation of mathematically embedded LCS in each shoulder bony segment, subjects with SIS moving through arm elevation in the scapula plane and flexion in the sagittal plane demonstrated increased posterior scapular tilting at 120^o scapula plane abduction, increased upward rotation at 90^o scapula plane elevation, and increased upward rotation between 90 and 120^o sagittal flexion.

The performance of the repertoire in the present study involved positions and motions unlike those used to assess three-dimensional kinematics associated with impingement in other studies. Most studies employed motion of the arm in the scapula plane (usually about 40^o forward of the coronal plane) with the humerus in neutral internal/external rotation, and the subjects were limited rotating the arm about its vertical axis in most cases. This study rather used an occupational task to assess the effects of the motion required to perform with the violin on SIS. Few of the anticipated motion and EMG factors that were thought to be associated with SIS were actually indentified in this study. The scapula was noted to tilt posteriorly and rotate upwardly, contrary to the hypothesized motion associated with SIS. The scapula was noted to internally rotate at both slow and fast speeds. The glenohumeral joint was also noted to move in a way unanticipated, with decreased flexion and increased external rotation being observed. It is possible that the relationship between the scapula and the humerus in terms of internal/external rotation may have been compensatory, since the scapula showed more internal rotation and the humerus more external rotation. This may have been the result of tight posterior glenohumeral joint structures, such as the posterior capsule (Borich et al, 2006).

Speed differences were distinctly noticeable in the graphs presented for all scapula and glenohumeral EVAs (Figures 4.1 through 4.6) and correspondingly high odds ratios were identified using mixed-effects multinomial logistic regression statistics (Tables 4.8 to 4.19.), indentifying high odds ratios for cells 1, 2 and 3 in most cases, representing short durations of time spent at particular amplitude levels during performance. These results indicate that the EVA technique was consistently able to differentiate between fast and slow repertoire performance, hence supporting hypothesis 2.

The etude that was played required several crossings from E to G strings (see Figure 3.13) and in the fast repertoire, the repetition of these crossings was 8 times more frequent, since the fast repertoire was the slow score played through 8 times at a significantly faster speed, with both fast and slow trials lasting 30 seconds. It therefore appears evident that injured and uninjured participants consistently played with less glenohumeral flexion. This string crossing requirement governed the musicians' choice of motion and it is possible that few of the kinematic trends seen in other populations that were investigated for SIS (Lukasiewicz et al, 1999; Ludewig and Cook, 2000;

Graichen et al, 2001; and Endo et al, 2001) were identified as being associated with SIS because of the task being performed. It is possible that people in other occupations move similarly to those in the current study, but they were analyzed performing a task requiring them to raise their arm overhead rather than play a violin. Ludewig and Cook (2000) performed their study on construction workers who particularly work overhead, and it is possible that the trends seen in that study bear little resemblance to those identified in the current study.

The findings of the present study are consistent with Deutsch et al (1996), Paletta et al (1997), Graichen et al (2001), Yamaguchi et al (2000), and Mell et al (2001) with respect to scapular rotation. However, the motion behaviors reported by these authors were associated with confirmed rotator cuff tears, and no conclusive diagnostics were performed in the present study to verify the status of the rotator cuff or other subacromial structures. The findings in the present study are also inconsistent with those of McClure et al (2006), who found that those with SIS demonstrated increased upward rotation and posterior tilting during scapula plane elevation, and increased upward rotation during glenohumeral flexion at 90^o and 120^o. The findings of the present study are also inconsistent with those of Ludewig and Cook (2000), Endo et al (2001), and Lin et al (2006) with respect to scapula tilting and upward rotation. The findings are consistent with those of Hebert et al (2002) and Ludewig and Cook (200) with respect to scapular internal rotation.

Apart from Ludewig and Cook (2000), who found that subjects with impingement showed decreased scapula upward rotation after 60^o of scapula plane abduction, all other studies observed significant differences in scapula motion between groups only after 90^o

of glenohumeral abduction. A more traditional method of analysis using the data from the present study to assess scapulothoracic and glenohumeral variables on a temporal scale for motion between 50^o and 65^o of arm elevation during musical performance, failed to identify significant differences between injured and uninjured musicians. This motion range is thought to be more risky in terms of SIS, particularly if one considers that the musicians studied, unlike those in aforementioned research who performed scapular plane abduction in a position near neutral internal/external humeral rotation, also adopted a position of internal rotation of the upper arm (arm plane elevation). However, such analysis failed to identify any significant differences between the two groups using two-way analysis of variance, with speed (fast and slow) and injury (injured and uninjured) as main effects (Tables 4.24 to 4.31). This may be explained by the fact that abnormal scapular rotations that were associated with injury in previous research were only significant at or above 90^o of arm elevation. Yet the EVA analysis adopted in this study indicated that almost the opposite motions of the scapula relative to the trunk, and the humerus relative to the scapula were found to be associated with injured musicians below 90^o abduction. It is possible that the combined motion of the shoulder into glenohumeral elevation and internal rotation, with scapula internal rotation, produces a position of near anterior impingement, and the injured musicians play in a compensatory fashion to off-set this potentially harmful posture. It is also possible that they did not have the more classically described anterior impingement, but rather an internal impingement. Internal impingement may have occurred in the injured participants in this study with a combination of internal rotation of the scapula and external rotation of the glenohumeral joint which has been found to have an association with internal impingement (Paley et al, 2000).

Ludewig and Cook (2000) found that injured participants displayed decreased posterior scapular tilting at and above 120^o, and reduced upward rotation at 60^o of scapular plane abduction. Endo et al (2001) and Su et al (2004) also reported increased scapula downward rotation with arm elevation. Endo et al (2001), used a two-dimensional radiographic technique, and Su et al (2004) used a handheld inclinometer, both measuring in one plane only, as opposed to the 3-D methodology used by Ludewig and Cook (2000) and McClure et al (2006). Lukasiewicz et al (1999) also found that subjects with subacromial impingement syndrome had a tendency to show reduced posterior tilting in the scapula with arm elevation. Hebert et al (2002), using an optical 3-D kinematic methodology, found that increased internal rotation of the scapula during flexion at the glenohumeral joint was evident in those with impingement. They concluded that the scapula contribution to shoulder motion varies, depending on the motion (flexion or abduction); however, none of the other scapula motions was statistically significant in the SIS group for either arm motion.

When the exposure variation analysis (EVA) methodology was used, and the task was one that more closely resembled an occupational activity, as opposed to a movement confined to one plane, the EVA technique appeared to be a useful data reduction technique in identifying what appear to be compensatory motions associated with SIS. Musicians performed in positions of arm elevation below 65^o much of the time. Moreover, the analysis was also able to discern factors associated with duration spent at different motion amplitudes. In the field of ergonomics, quantification of exposure to risk is an important tool in identifying factors that predispose humans to injury. It was evident in the present study that the assessment of motion alone was not sufficient in identifying factors that could be associated with SIS, yet when that risk was quantified in terms of periods of time spent at various motion amplitude strata, it was discovered that musicians did not move in ways that have previously been thought of as contributory to SIS.

It is possible that the injured musicians seen in this study were predisposed to SIS for other reasons, such as tissue integrity (Soslowski et al, 2002), scapula morphology (Zuckerman et al, 1992; Farley et al, 1994; Bigliani and Levine, 1997), soft tissue tightness (Borstad and Ludewig, 2005; Kibler, 1998; Borich et al, 2006), or thoracic posture (Kebaetse, 1999). Injured musicians in this study were noted to play with decreased posterior tilting of the scapula, and therefore it is unlikely that they would have presented with tight or short pectoralis minor on the right side (Borstad and Ludewig, 2005). Injured musicians in this study were noted to play with increased scapular internal rotation and, perhaps in a compensatory manner, less glenohumeral external rotation, perhaps because of tight posterior glenohumeral joint tightness (Borich et al, 2006). Most of those with SIS were noted to have positive Hawkins-Kennedy impingement tests, but the principal investigator did not inquire as to the location of the pain relative to the anterior or posterior aspect of the shoulder. It is possible that musicians reporting pain on the Hawkins-Kennedy impingement test were actually feeling the pain posteriorly and internally, rather than anteriorly, and that their impingement was more internal and related to soft tissue tightness, rather than that induced by excessive upper trapezius and less serratus anterior use as was hypothesized. No differences were found between the two groups in terms of thoracic kyphosis posture at rest, as was hypothesized to be the case by Kebaetse (1999), although in the Kebaetse study, thoracic motion limitations were found with maximum attempts at forward trunk flexion rather than resting posture.

Observations and Conclusions: Electromyographic Data

Research using surface EMG on a group of violinists with and without shoulder injury revealed high levels of upper trapezius EMG but not in the injured group (Berque and Gray, 2002). These findings are contrary to those of Philipson (1990) who found that upper trapezius EMG was associated with shoulder injury. Differences in these two studies may be explained by differences in normalization technique; Berque and Gray used upper trapezius normalization methods comprising comparison of performance task EMG activity to that measured during a standardized task referred to as the relative voluntary electrical activity as described by Mathiassen and Winkel (1995). A similar method of EMG normalization was used in the present study. It should be noted that Berque and Gray (2002) did not specify shoulder injury diagnoses in their injured sample and their injured group may not have been homogenous with the sample that was used in the present study. However, a more important difference is that they used mean EMG as a measure of exposure to risk. Mean EMG does not suitably identify the fluctuation of the EMG signal over time. The signal may fluctuate significantly, or it may not fluctuate at all and one may end up with the same mean without knowing the signal's behavior for the task. If we assume that the diagnoses for this study match those of the sample in the Berque and Gray (2002) study, then the results of the mean EMG analysis are in agreement. Injured musicians in the current study were noted to utilize less upper trapezius activation and their utilization of upper trapezius was characterized by shorter duration activation rather than long or sustained duration activation. The results of the current study are not in agreement with the findings of Philipson et al (1990), who found that those with shoulder injury played with higher levels of upper trapezius EMG.

The principal method of analysis in the present study was the exposure variation analysis (EVA) method proposed by Mathiassen and Winkel (1991). The results in this study indicate that violinists in the injured group used more serratus anterior activation and decreased upper trapezius activation at both slow and fast speeds. It is possible that, as may be the case in kinematic analysis, they move in a compensatory fashion to alleviate discomfort, and it is possible that the cause for SIS is dependent on other factors.

Musicians are limited by the design of the instrument and the rigors of traditional pedagogy, and conforming to these traditional methods of performance, with the arm held relatively static between narrow ranges of glenohumeral flexion, abduction and internal rotation, coupled with relatively limited motion in the scapula (compared to motions studied by others, Ludewig and Cook (2000), Graichen et al (2001), Lukasiewicz et al (1999)) may impose positions that are not tolerated by some, and this study has identified those who have poor tolerance for the activity, and are therefore forced to compensate. Soslowski et al (2002) described intrinsic tendon degeneration from eccentric overload in rats, and also cited age, ischemia or inferior tissue property as being likely intrinsic causes of SIS. It is also possible that musicians cause trauma to the subacromial space by virtue of their performance, and some are able to withstand these assaults on the soft tissues in the subacromial space and others not. It has been shown that simulated rotator cuff tears will result in compensatory upward rotation of the scapula after suprascapular nerve block (McCully et al, 2006), and musicians are possibly moving in the same way. Musicians in this study did not perceive their pain to be too severe, with Shoulder Rating Questionnaire rating to be 75% for injured participants and 95.6% for uninjured, and the visual analog scale average was 2.1 for injured participants and 1.2 for uninjured ($p<0.01$ for both analyses). This may explain why the changes see in kinematic analysis are sometimes subtle, and in some cases not necessarily clinically relevant.

Increased upper trapezius activation and decreased serratus anterior activation have been associated with subacromial impingement syndrome (SIS) (Ludewig and Cook, 2000), though as in the kinematic analysis, significant differences were seen only in the upper ranges of scapula plane abduction. In the present study, similar significant differences were found in the analysis performed for the 50^o to 65^o range of scapula plane abduction for upper trapezius, and these effects were not attributable to either fast or slow speeds. This suggests that with an occupational task, the effect of EMG in the upper trapezius is more noticeable in those with SIS. It should also be noted that none of the kinematic variables were significant in terms of main effects for injury using two-way analysis of variance. The results of the EVA analysis indicated that injured participants in fact used less upper trapezius activation, and did so with more dynamic (short durations of activation). Such brief low activation periods have been found to be associated with those without shoulder pain (Veiersted et al, 1993), and therefore the results of the present study do not agree with this theory. It should be noted that Veiersted et al (1993) looked at gaps in the EMG signal characterized by very short duration periods of time (0.2 to 2 seconds) spent at very low EMG amplitude (0.5% maximum voluntary electrical activity (MVE)). The reduced recruitment of upper trapezius appears to be compensatory therefore, since injured musicians were found to show more upward rotation and posterior tilting, probably in an effort to decompress the subacromial space. The findings of this study with respect to upper trapezius activation alone are similar therefore to those of Berque and Gray (2002), however, this similarity needs to be viewed in the context of the differences in methodology as mentioned above.

Serratus anterior EMG was found to be increased in injured participants performing at both slow and fast speeds, contrary to what was anticipated. More traditional two-way analysis of variance statistics on mean EMG (group (injured and uninjured) and speed (fast and slow)) failed to identify a difference between the two groups in the analysis of arm elevation between 50^o and 65^o in the present study (Table 4.31). The EVA technique was therefore instrumental in simultaneously identifying increased amplitude and longer time period activation of the serratus anterior, but as in upper trapezius, this does not explain the mechanics associated with impingement. The serratus anterior muscle is responsible for posteriorly tilting, upwardly rotating, and externally rotating the scapula during arm elevation, and its activation pattern in this study matches the increased upward rotation and posterior tilting seen in the kinematic analysis. Once again, this may be a compensatory activation to reduce impingement in those injured participants, and does not seem to provide explanation for their injured status.

Data Analysis Methodology: Exposure Variation Analysis (EVA)

Several researchers have used the exposure variation analysis method to quantify relative risk associated with such dependent variables as range of motion and myoelectric activity relative to frequency (Anton, 2002b; Mathiassen and Winkel, 1991; Mathiassen and Winkel, 1996; Bao et al, 1997; Hägg et al, 1997; Hägg and Åström, 1997). None of these, however, acknowledged the correlation structure within the EVA array. They chose instead to adopt normal parametric statistics (multiple analysis of variance) and log-linear regression methods (Jansen et al, 2001) to identify differences between arrays. The cells in the EVA array represent percentages or proportions of time spent at various “intensity” levels and time durations, and they are therefore not independent. Removing data in a column or row, as was suggested by Mathiassen and Winkel (1991), and which was also adopted by Anton (2002 b), does not adequately resolve the violation of independence since amplitude bins are more correlated with adjacent than with “distant” bins in the array, while adjacent time bins are not correlated.

Anton (2002 b) used a two-way mixed-effects repeated measures ANOVA to assess differences between clusters in EMG EVA arrays (CEVA) in a study of operating engineers and mechanics. Main effects of trade and EVA exposure category, as well as interactions between trade and exposure category, were assessed using general linear models. However, these methods are dependent on the assumption of independence as well and he was forced to eliminate rows and columns of data in the creation of the, “clusters” and to satisfy the assumption of independence.

The correlation structure of what is essentially a multinomial distribution must, however, be taken into consideration. Recently published mixed effects multinomial logistic regression statistical methods (Hedeker, 2003) provide a robust method of assessing the odds of the signal in a particular dependent variable being in a cell of the EVA array, as opposed to being in a reference cell, chosen *a priori*. This appears to be the first application of such methods in discerning differences between two groups (injured and uninjured) using EVA methods. All cells in the array were preserved except where standard errors were zero and cells were collapsed into one another for analysis.

One of the disadvantages of this method of analysis is its dependence on the work task being distributed to all cells in the array. Many of the cells in the 9 X 9 EVA arrays used by previous researchers (Mathiassen and Winkel, 1991; Mathiassen and Winkel, 1996; Bao et al, 1997; Hägg et al, 1997; Hägg and Åström, 1997) were empty, which would have forced the researchers to “collapse cells” (combine the contents of two or more cells and analyze them as one), as was the case in the present study.

Despite the absence of injury main effects for the analysis of kinematic variables for arm elevation between 50 and 65 degrees (using two-way analysis of variance), significant effects for injury were found in the EVA analysis of these same variables using the same data, employing the mixed effects multinomial logistic regression statistical methods (Hedeker, 2003). The EVA technique has been found to be a useful technique in simultaneously assessing range of motion excursion and repetition and has been used to establish the efficacy of ergonomic interventions in various assembly (Mathiassen Winkel, 1996; Bao et al, 1997), automobile assembly (Hägg et al, 1997), service (Jansen et al, 2001), and construction (Anton, 2002 b) industries.

EVA Limitation

The use of EVA methodology in the present study was instrumental in discerning differences between fast and slow repertoire as well as differences between groups with and without SIS, which more traditional temporal methods failed to do. Analysis of kinematic and EMG variables at arm elevation between 50^o and 65^o indicated that there were no differences between groups, yet the EVA method, together with mixed-effects multinomial regression analysis was able to discern differences between the two groups.

More importantly perhaps is the fact the this analysis was able to indicate that musicians did not move in ways that have previously been shown to be associated with SIS, but rather that they move in a more compensatory method presumably to avoid pain. The purpose of this evaluation was not to determine the causes of SIS, but rather to determine kinematic and EMG factors associated with injury, but it appears that the findings indicate more of a compensatory behavior than a causal one.

The EVA method, however, is dependent on the choices of bin margins for each axis. Choice of the EMG time period axis was particularly problematic because of the frequency distribution of the EMG and kinematic signals. Mathiassen and Winkel (1991) proposed use of a log base 2 scale of time period in a 9X9 EVA. Bao et al (1997) and Hägg et al (1997) used 0 to 0.3s and 0.3s to 1s as their lower 2 bin widths in a log base 2 time period scale, and these represent the lowest time period scales that have been published. EVA is, however, typically used in ergonomic analyses that span several hours, while it was used in the present study for only 30 seconds. This may explain the high frequency content of the EMG signal. The task was also relatively intense, with even experienced musicians expressing frustration at the speed of the fast repertoire. Ergonomic studies tend to focus on occupations such as assembly, housekeeping, nursing, and construction trades, which though they may have periods of high intensity work, are not typically as intense as was the fast repertoire performance in this study.

The appearance of the EVA array, as well as the frequency expression, is also dependent on the choice of amplitude margins. If the margins are too close together, as was the case when tertiles of the range were used in the uninjured group to determine amplitude margins, the frequency of crossings of these margins increases, giving the appearance of a higher frequency of performance. Such an observation may be erroneous.

The appearance of the EVA graphs in the present study seemed to describe the performance of the task adequately, and suitable statistical analysis, which has largely eluded previous researchers, generally agreed with the appearance of the data arrays. Use of the mixed-effects multinomial logistic regression statistical methods used in the present study will likely provide ergonomics researchers with a more suitable method of analyzing this useful data reduction technique in other occupations. Previous researchers have used multiple analysis of variance methods to analyze data. Doing so required them to eliminate rows and/or columns of data to satisfy the independence assumption. The methods used in this study account for the dependence of the cells by repeatedly estimating the covariance matrix within an iterative method known as maximum likelihood estimation within the array, and therefore all the data contributes to the outcome. The method used in this study is therefore proposed as a superior alternative to those used by other researchers who have previously used EVA methods.

Statistical Methodology for Determining EVA Differences: Mixed Effects Multinomial Logistic Regression

The proposed statistical methods for EVA analysis were abandoned in favor of a new method known as mixed-effects multinomial logistic regression (Hedeker, 2003; Hedeker and Gibbons, 2006). The method appeared to satisfactorily indentify the differences in speed and amplitude that were observable in the graphs that depicted each of the kinematic and EMG variables. The reliability of the method was found to be high, with most ICCs being above 0.80, and the standard error of the measurement values were comparatively low.

The assessment of covariates in the analysis resulted in a significant increase in computation time. Inclusion of factors such as age, a continuous variable, and gender resulted in more than 7 hours of computation time per dependent variable. When comparing effects of these analyses to original analyses, no substantive alterations in findings were identified.

Limitations of the Study

Despite the fact that this study was successful in confirming the reliability of the EVA technique, its ability to discern speed differences in 3-D kinematic shoulder analysis, and the identification of altered scapular and glenohumeral motions in the injured group, some limitations exist in this type of research, and this study was no exception.

1. Kinematic analysis is inefficient in terms of random access memory (RAM) use, and trials of performance were limited to 30 seconds by this factor alone. SIS is apparently caused by repetitive strain. Joint kinematics and myoelectric activity are likely to change over the course of a practice or performance session, perhaps leading to more significant changes in kinematic and EMG exposure. Analysis for 30 seconds may therefore have limitations in discerning the effects of playing.
2. The three-dimensional kinematic analysis for this study was performed using surface mounted sensors. These are prone to more error than would be the case if the sensors were mounted to bone pins secured into bicortical bone segments.

Recruitment of participants for invasive research such as this is problematic and would probably provide little gain in comparison to that lost in numbers of participants. Karduna et al (2001) found suitable agreement in the comparison between bone pin mounted sensors and surface mounted sensors. To minimize error, the scapula sensor was mounted to a custom made jig in their study when the motion was below 90^o humerothoracic elevation. Scapula titling and upward rotation had better agreement in this regard than did internal/external rotation.

3. Motion at the clavicle was not assessed in this study, and given that the results of this study were contrary to what was expected, it may have been useful to have evaluated clavicular motion, particularly considering the inactivity of upper trapezius in the injured participants.
4. Some of the amateur musicians struggled to perform the fast repertoire, and their accuracy in performance was not optimal. Some musicians arrived unprepared for the performance of the repertoire, despite having been sent the musical score and an audio clip of the music, together with instructions on performance requirements on the day of testing. The precision of the measurement of EMG and kinematic variables in the task performed helps to establish the reliability of the technique. The fast repertoire was difficult to play and may have introduced some error into the measured accuracy of the EVA technique.
5. No actual diagnostic testing was performed on participants, other than the clinical examination mentioned in Chapter 3. Musicians were divided into injured and uninjured groups based on this examination, and actual diagnostic imaging may have altered the group delineation. Based on the pain assessment alone, the injuries in the injured participants were mild. Stratifying musicians into more than

one injury group may add to the significance of the trends seen in the injured group in the present study.

6. Several instrument dimensions, including violin weight, were measured for the present study; however, the weight of the bow was not measured. The average weight of a violin bow is 60 g, with a range of 54 g to 66 g (*Strings*, 2004). None of the instrument dimensions in this study were significantly different when the two groups were compared, yet inclusion of this measurement should be considered in future research.
7. Age and gender were found to be significantly different in the two groups in this study. Separate covariate analysis including age and gender in the regression model with speed and injury failed to provide any differences not already explained by injury, and injury* speed interactions reported.
8. It is possible that upper trapezius and serratus anterior are not sensitive to muscle recruitment differences in the two groups in this study. Assessment of rotator cuff musculature, such as subscapularis, infraspinatus, supraspinatus and teres minor may be necessary to ascertain potential differences in muscle activity that may explain group differences. The subscapularis and infraspinatus serve to inferiorly translate the humerus relative to the glenoid and inadequate recruitment of these muscles may reveal more about glenohumeral biomechanics than upper trapezius and serratus anterior.
9. Translations of the humerus along the various axes were measured but not reported in this study. It is possible, as is mentioned in 8 above, that these translations may explain biomechanical factors that could explain differences between the two groups in this study.

Summary of the Study

This study has been successful in furthering the utility of the exposure variation analysis (EVA) data reduction method, and in providing a more optimal method of establishing statistical differences between groups being analyzed with respect to exposure to potentially harmful ergonomic risk factors. The method was found to have high repeatability (mostly greater than 0.75 ICC (85%) and low standard error of the measurement (SEM), mostly less than 10% (88%)). The method was successful in identifying repertoire speed differences.

Injured musicians utilized shorter durations of lower upper trapezius activity than their uninjured counterparts in the performance of fast and slow repertoire. Injured musicians were also noted to use greater amplitude and longer duration of serratus anterior activation at both slow and fast speed performance.

Contrary to what was expected, injured musicians also adopted positions of less anterior scapular tilting and greater scapular upward rotation than uninjured musicians, and injured musicians played with greater internal scapular rotation than uninjured musicians. Perhaps as a compensatory strategy, the injured musicians were also noted to play with less glenohumeral flexion, and less internal rotation. The muscle recruitment pattern of the serratus anterior and the upper trapezius was consistent with the kinematic variation that was seen.

The results of this study seem to indicate that muscular strengthening of the serratus anterior will provide little benefit to violinists with SIS in an effort to alleviate discomfort and treat the SIS. It appears that they would do better to focus their attention on postural “setup”. Strategies that may be of benefit are as follows:

1. Tilting the instrument anteriorly so that performance on the G and D strings, particularly in up bow positions, requires less arm elevation. This can be achieved in two ways:
    a. Raising the posterior aspect of the shoulder rest (see Figure 3.3) and lowering the anterior aspect of the shoulder rest. This is a temporary method and can be performed as a trial to test the efficacy of the intervention.
    b. A luthier (violin-maker) is able to re-set the neck of the instrument to tilt the neck forward very slightly. Longstanding string tension on an older violin can angle the neck up and forward over time, and may need to be re-adjusted from time to time.
2. Holding the instrument closer to the sagittal plane and less in the coronal plane (achieved by internally rotating the left shoulder) may also help them to avoid the cross-body action (achieved with greater glenohumeral flexion, arm plane elevation and varying amounts of both glenohumeral and scapular internal rotation) that is required if they play up bow on G and D strings.
3. Adopting a position of less abduction of the arm and utilizing the weight of the arm to apply force of the bow in the string, rather than using an internal glenohumeral rotation and pronated forearm action to do this.
4. Excessive forward flexion at the trunk results in increased anterior tilting of the scapula (Kebaetse et al, 1999) and possibly results in adaptive shortening of the pectoralis minor (Borstad and Ludewig, 2005). Therefore, correction of

increased thoracic kyphosis may lead to improved subacromial clearance and reduce the musician's predisposition to SIS.

The injured musicians had low pain reports and high Shoulder Rating Questionnaire reports, indicating that these injuries were perceived to be mild. Yet significant compensatory motions and muscle recruitment features were identified. The musician is required to perform with an ergonomically inefficient instrument, and they are not easily able to modify their work task in terms of repetition, speed, intensity or position. Injuries are reportedly common (greater than 60% in professional musicians report performance limiting injury), yet they are reluctant to report the injury for various reasons. These factors may be significant in terms of causation, and the movement and muscle recruitment strategies seen in this study appear to reflect only compensatory strategies that they adopt to avert pain.

Recommendations for Further Study

1. Future research into the injuries seen in this population may best be performed in a longitudinal design. Assessing a group of freshman students in a large metropolitan music conservatory and following them over time may prove to be beneficial. Students at this level have the requisite skill to perform repertoire of the type used in this study. More importantly, students arriving at a university have probably been practicing for 1-2 hours a day, yet once they start in a conservatory/university setting, their practice and performance time increases and they are more predisposed to injury as a result. Several studies investigating injury prevalence in musicians have been performed in university settings.

Longitudinal research would allow for the determination of causal factors associated with injury rather than merely seeking kinematic and EMG factors that may be associated with injury.

2. Future research should be performed using actual musical scores. The EVA technique has been found to be reliable method of analysis in this study, and that is sensitive to speed. With the resolution of the RAM limitations on the computer, performance of actual music score(s) for longer durations of time may be useful in ascertaining the causal factors associated with injury.
3. Since the technique used in this study has been found to be a reliable representation of the performance exposure with a violin, the technique will probably be useful in the determination of similar pathologies in other musician groups. Care needs to be exercised to avoid assessing musicians who play instruments that comprise ferrous metals due to the possible interference of these metals with the kinematic electromagnetic transmitter.
4. EMG data could be assessed with a data logger in actual performance situations. Data loggers are small and can be worn on a belt, much like a pager. The electrodes are non-invasive and the electrode leads can be hidden under clothing, making detection of the device difficult to the untrained eye. EVAs are created in real time and are merely downloaded to a computer at the end of the performance task.
5. EMG study of the rotator cuff, possibly using fine wire needle electromyography, needs to be considered to gain a better understanding of the shoulder muscle recruitment patterns during performance.

6. Future study of shoulder biomechanics during violin performance needs to include humeral translations that can be matched with rotator cuff EMG to further explain glenohumeral motion during violin performance.

APPENDIX A

Consent Form

Shoulder Joint and Muscle Exposure in Violin Musicians: a Three Dimensional Kinematic and Electromyographic Exposure Variation Analysis

You are invited to participate in a research study to help determine the causes of Subacromial Impingement Syndrome sustained by violin musicians. Subacromial Impingement Syndrome is a term which encompasses rotator cuff tendinitis and bursitis in the shoulder. This study is being performed by Jonathan Reynolds MSc, PT in the program in Physical Therapy, Department of Physical Medicine and Rehabilitation at the University of Minnesota. You were selected as a possible participant because you are a violin musician with at least 15 years experience with the instrument and because you have indicated that you are proficient in the performance of an etude written especially for this research study. In addition, you have asserted that you have no metallic implants in your head, upper extremities or upper torso.

Background Information:

The purpose of this study is to identify the shoulder joint and muscle activity during performance with the violin instrument and how this may be related to right-sided shoulder impingement. This information will assist us in determining possible causes of injury in musicians who are experiencing discomfort or who have injuries. This may also assist us in developing treatment and injury prevention strategies for musicians with shoulder problems, and therefore help to reduce the large numbers of musicians who terminate promising careers or who continue to play with shoulder discomfort.

Procedures:

If you agree to participate in this study, we would ask you to do the following things: Provide background information to the investigator (age, height, weight; performance history, practice times and experience as well as instrument measurements, which the investigator will perform with your assistance).

If you report shoulder or neck pain at any time during the study you will receive a clinical screening of your shoulder motion, tenderness, and muscle function.

The data collection procedure will involve placing sensors on muscles and bony areas around your right shoulder. These will be attached using double sided adhesive tape in much the same way that a Band-Aid is attached. You will then be given an opportunity to play your instrument to become accustomed to playing with the sensors in place, and this will also serve as a warm up. Following this you will be asked to play 8 trials of the etude played at two different speeds: these 8 trials will be played in random order. This will complete the study.

Risks and Benefits of Being in the Study:

The study has risks, although minimal. First, the testing may result in mild muscle or joint soreness from contracting muscles. This is unlikely considering that you will be playing your instrument for about 30 minutes during the hour of data collection. Second, you may be allergic to the adhesive tape. Lastly, this testing may involve risks to you that are currently unforeseeable.

There are no immediate benefits to you for your participation in this study. Information gathered from the study may assist in designing future research studies to further determine the causes of right sided shoulder injuries seen in violinists and violists.

Compensation:

For each test session, you will receive a payment of $20 to compensate you for your time. Your parking costs for the duration of the study will be reimbursed.

Confidentiality:

The records of this study will be kept private in accordance with Federal HIPAA regulations. In any sort of report we might publish, we will not include any information that will make it possible to identify you as a participant. Faculty members/officers in your orchestra will not be notified regarding your participation in this study or of any specific medical findings discovered as part of this study.

Voluntary Nature of the Study:

Your decision whether or not to participate will not affect your current or future relations with the University or your organization. If you decide to participate, you are free to withdraw from the study at any time.

New Information:

If, during the course of this research study, there are significant new findings discovered which might influence your willingness to continue, the investigator will inform you of those developments.

Contacts and Questions:

The researcher conducting this study is Jonathan Reynolds. Jonathan is a physical therapy graduate student at the University of Minnesota. You may ask any questions you have now. If you have questions later, you may contact him at the Program in Physical Therapy, Box 388 Mayo, The University of Minnesota, Minneapolis, MN 55455; Phone: (612) 625-7930 or (612) 432-3244. If you have any questions or concerns regarding the study and would like to talk to someone other than the researchers, contact Patient Relations Department, B-310 Mayo Memorial Building, 420 Delaware Street SE, Minneapolis, MN, 55455; telephone (612) 273-5050.

You will be given a copy of this form to keep for your records.

Statement of Consent:

I have read and understand the above information. I have asked questions and have received satisfactory answers to these. I hereby give consent to participate in the study.

Participant Signature ______________________________ Date ___________

Signature of Principal Investigator ______________________Date ____________

APPENDIX B

Participant Questionnaire and Evaluation Form

Shoulder Joint and Muscle Exposure in Violin Musicians

Participant Number (please leave blank)	
Date	/ /200
Date Birth (mm/dd/yyyy)	/ /19
Gender (circle one)	F M
Height (ft ins)	Ft. ins.
Weight (lbs.)	Lbs.
Hand Dominance (circle one)	R L

		Hours Per Week		
Instrument(s)	Years Playing	Practicing	Performing	Teaching
1. Violin				
2.				
3.				
4.				

Previous Performance Limiting Injury(s)?

Area(s) injured	Date of Injury	Is/are the injury(s) resolved?		If not, explain
		Y	**N**	
		Y	**N**	
		Y	**N**	

Health:

Do you use tobacco products?…………………………….............	Yes ☐	No ☐
Do you consume alcohol?…………………..............................……..	Yes ☐	No ☐
Do you use, or have you ever used, beta-blocker medication?.....	Yes ☐	No ☐
Do you suffer from any of the following medical disorders?		
Arthritis………………………………………………………...............	Yes ☐	No ☐
Diabetes…………………………………………………………............	Yes ☐	No ☐
Gout…………………………………………………………………...........	Yes ☐	No ☐
Thyroid Problems……………………………………………...............	Yes ☐	No ☐
Systemic Lupus Erythematosis…...............................……..............	Yes ☐	No ☐
Tendinitis………………………………………………………..................	Yes ☐	No ☐
DeQuervain’s Disease………………………………………..............	Yes ☐	No ☐
Carpal Tunnel Syndrome……………………………………..........	Yes ☐	No ☐
Thoracic Outlet Syndrome………………………………..............	Yes ☐	No ☐
Cubital Tunnel Syndrome………………………………..............	Yes ☐	No ☐
Neurological Disorders………………………………………............	Yes ☐	No ☐
Lateral Epicondylitis (Tennis Elbow)………………………...............	Yes ☐	No ☐
Medial Epicondylitis (Golfer’s Elbow)……………………..............	Yes ☐	No ☐

Don’t write below this line

Physical Examination

	Left	Right	
Posture			**Comments**
Scapula Downward Rot.	+ -	+ -	
Scapula Medial Rot.	+ -	+ -	
Scapula Anterior Tilt	+ -	+ -	

Active Range of Motion			**Comments**
Thoracic Neutral Posture		Degrees	
Shoulder Flexion			Degrees
Shoulder Abduction			Degrees
Shoulder LR			Degrees
Shoulder MR			Degrees

Manual Muscle Tests			**Comments**
Shoulder External Rotation	1 2 3 4 5 P	1 2 3 4 5 P	
Shoulder Internal Rotation	1 2 3 4 5 P	1 2 3 4 5 P	
Shoulder Abduction	1 2 3 4 5 P	1 2 3 4 5 P	

Special Tests			**Comments**
Neer	+ -	+ -	
Hawkins-Kennedy	+ -	+ -	
Speed	+ -	+ -	
Jobe	+ -	+ -	
Painful Arc	+ -	+ -	
Subacromial Impingement Syndrome	+ -	+ -	

Outcomes		
Visual Analog Scale		cm
Shoulder Rating Questionnaire		%

Instrument Assessment			**Comments**
Overall Length		mm	
Weight		mm	
Bridge to Scroll Length		mm	
Bridge Height		mm	
Bow Length		mm	
Active Neck Height		mm	

APPENDIX C

Visual Analogue scale

Make a mark (---) across the line below to indicate how severe the pain in your right shoulder is RIGHT NOW between the extremes of, “No Pain at All” at the bottom of the line and, “Pain as Bad as it Could Be” at the top of the line.

Pain as Bad as it Could be

No Pain at all

APPENDIX D

Musical Repertoire

Frisch Etudes

Violin Etude - Slow

Mira Frisch

Violin Etude - Fast

Mira Frisch

(repeat 8 times)

APPENDIX E

EVA SAS code

The following code was used to create the exposure variation analyses. The code would need to be modified for each dependent variable.

```
/*
Input data set evaprepN where N is a subject id consists of columns

id = subject id
trial = 1-4
speed = 0-1
subframe = 0-2999 (time from 1-3000 for a single 30 second trial)
variable name = raw data for variable at each time point for each trial


Sample call: Create EVA for RUT emg data, subject=13, speed=1, trial=4

   %makeeva(13,"rutemgn",1,4);

Creates output data set eva.

The code for kinematic variables is the same, with different time and amplitude cutoffs.
*/


%macro makeeva(subj,varnm,speed,trial);

data tmp;
set inlib.evaprep&subj;
if trial=&trial and speed = &speed;
run;
proc sort;
by subframe;
run;

data evaseg&subj._&varnm._&speed._&trial;
set tmp end=lastrec;
/* set cutoffs for forming the eva based on amplitude of the variable (cutoff)
and time boundaries for short-medium-long segments (tcutoff)
*/
array cutoff(2) (0.5 1.0);
array tcutoff(2) (10 30);
id=&subj;
speed=&speed;
trial=&trial;
varnm = "&varnm";
retain timecount vclass;
if . < &varnm le cutoff1 then newclass=1;
else if cutoff1 < &varnm le cutoff2 then newclass=2;
else if cutoff2 < &varnm then newclass=3;

if _N_ eq 1 then do;
   timecount=1;
   vclass=newclass;
end;
else if lastrec ne 1 then do;
  if newclass eq vclass then timecount=timecount+1;
```

```
  else do;
    if . < timecount le tcutoff1 then tclass=1;
       else if tcutoff1 < timecount le tcutoff2 then tclass=2;
       else if tcutoff2 < timecount then tclass=3;
       output;
       vclass=newclass;
       timecount=1;
  end;
end;
else if lastrec eq 1 then do;
  if newclass eq vclass then timecount=timecount+1;
  else do;
     if . < timecount le tcutoff1 then tclass=1;
     else if tcutoff1 < timecount le tcutoff2 then tclass=2;
     else if tcutoff2 < timecount then tclass=3;
     output;
     vclass = newclass;
     timecount=1;
  end;
  if . < timecount le tcutoff1 then tclass=1;
     else if tcutoff1 < timecount le tcutoff2 then tclass=2;
     else if tcutoff2 < timecount then tclass=3;
     output;
 end;
keep id varnm speed trial vclass tclass timecount;
run;

/* The breakdown macro creates a data set with a single observation in which summary
statistics for the variable
var are broken down by several class variables.  Here tclass represents the time duration
class (1-3) and vclass
represents amplitude class (1-3).  The variables are ordered so that evaclass =
3*(tclass-1)+vclass.
*/
%breakdn(data=evaseg&subj._&varnm._&speed._&trial,class = tclass 3 vclass
3,var=timecount,out=outset,print=no);

data eva;
set outset;
format varnm $10.;
tot = sum(of sum1-sum9);
id = &subj;
trial=&trial;
speed=&speed;
varnm="&varnm";
/* the replace macro creates lines of code based on a pattern in the list;
for i=1 to 9, the line written is of the form eva?=sum?/tot where ?=i. */

%replace(list= 1 2 3 4 5 6 7 8 9,target = eva? = sum?/tot);
 if missing(eva1) then eva1=0;
 if missing(eva2) then eva2=0;
 if missing(eva3) then eva3=0;
 if missing(eva4) then eva4=0;
 if missing(eva5) then eva5=0;
 if missing(eva6) then eva6=0;
 if missing(eva7) then eva7=0;
 if missing(eva8) then eva8=0;
 if missing(eva9) then eva9=0;
run;
%mend;
```

APPENDIX F

Instrument Calibration Study

JTech Medical Industries: Digital Goniometer (RangeTrack™)

Date	Full Scale Measurement	Linearity	Repeatability	Measured Accuracy	Hysteresis
March 25th, 2002	120.090°	-0.698%	0.693%	-1.146 to -0.243%	0.694%
October 23rd 2004	159.758°	0.401%	-0.784%	-0.554 to 0.641%	-0.784%

JTech Medical Industries: Dual Digital Inclinometer (Dualer™)

Date	Full Scale Measurement	Linearity	Repeatability	Measured Accuracy	Hysteresis
March 25th, 2002	101.70°	-3.034%	5.801%	-4.818 to 1.917%	4.834%
October 23rd 2004	119.36°	0.691%	1.404%	-0.814 to 0.825%	2.105%

Dual Inclinometer Calibration Tables

		Up			Down			Up			Down			Up			Down			Up					
Measurand	**Predicted (Regr.)**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Up Avg Er**	**Down Avg Er**	**Avg Error**
50.0	51.90	47.000	-4.900	-4.818				47.000	-4.900	-4.818				47.000	-4.900	-4.818							**-3.614**	**0.000**	**-1.807**
40.0	41.73	37.000	-4.730	-4.651	39.000	-2.730	-2.685	37.000	-4.730	-4.651	39.000	-2.730	-2.685	37.000	-4.730	-4.651	39.000	-2.730	-2.685				**-3.488**	**-2.685**	**-3.086**
30.0	31.56	27.000	-4.560	-4.484	29.000	-2.560	-2.518	27.000	-4.560	-4.484	29.000	-2.560	-2.518	27.000	-4.560	-4.484	29.000	-2.560	-2.518				**-3.363**	**-2.518**	**-2.940**
20.0	21.39	17.000	-4.391	-4.317	21.000	-0.391	-0.384	17.000	-4.391	-4.317	21.000	-0.391	-0.384	17.000	-4.391	-4.317	21.000	-0.391	-0.384				**-3.238**	**-0.384**	**-1.811**
10.0	11.22	8.000	-3.221	-3.167	11.000	-0.221	-0.217	7.000	-4.221	-4.150	12.000	0.779	0.766	7.000	-4.221	-4.150	11.000	-0.221	-0.217				**-2.867**	**0.111**	**-1.378**
0.0	1.05	0.000	-1.051	-1.033	1.000	-0.051	-0.050	3.000	1.949	1.917	1.000	-0.051	-0.050	-3.000	-4.051	-3.983	2.000	0.949	0.933	-3.000	-4.051	-3.983	**-1.771**	**0.278**	**-0.747**
-10.0	-9.12				-9.000	0.119	0.117	-13.000	-3.881	-3.816	-9.000	0.119	0.117	-14.000	-4.881	-4.799	-9.000	0.119	0.117	-13.000	-3.881	-3.816	**-3.108**	**0.117**	**-1.496**
-20.0	-19.29				-19.000	0.289	0.284	-23.000	-3.711	-3.649	-19.000	0.289	0.284	-23.000	-3.711	-3.649	-19.000	0.289	0.284	-23.000	-3.711	-3.649	**-2.737**	**0.284**	**-1.226**
-30.0	-29.46				-29.000	0.459	0.451	-33.000	-3.541	-3.482	-29.000	0.459	0.451	-32.000	-2.541	-2.499	-30.000	-0.541	-0.532	-32.000	-2.541	-2.499	**-2.120**	**0.123**	**-0.998**
-40.0	-39.63				-39.000	0.628	0.618	-42.000	-2.372	-2.332	-39.000	0.628	0.618	-42.000	-2.372	-2.332	-40.000	-0.372	-0.365	-42.000	-2.372	-2.332	**-1.749**	**0.290**	**-0.729**
-50.0	-49.80				-49.000	0.798	0.785				-49.000	0.798	0.785				-50.000	-0.202	-0.198				**0.000**	**0.457**	**0.229**

Full Scale = 130.38 - 10.29 = 101.700

Linearity = 0.215/101.7*100 = -1.355 %

Repeat. = (0.455- 0.010)/101.7 *100 = 5.801 %

Meas. Acc = -4.818 to 1.917 %

Hysteresis = -0.66 %

October 23rd 2004		Up			Down			Up			Down			Up			Down			Up					
		Obs	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Up Avg Er**	**Down Avg Er**	**Avg Error**
60	59.75	60.000	0.252	0.212				59.000	-0.748	-0.626				60.000	0.252	0.212							**-0.051**	**0.000**	**-0.025**
50	49.80	50.000	0.199	0.167	50.000	0.199	0.167	49.000	-0.801	-0.671	51.000	1.199	1.004	50.000	0.199	0.167	50.000	0.199	0.167				**-0.085**	**0.446**	**0.181**
40	39.85	39.000	-0.855	-0.716	41.000	1.145	0.959	39.000	-0.855	-0.716	40.000	0.145	0.122	40.000	0.145	0.122	40.000	0.145	0.122				**-0.328**	**0.401**	**0.037**
30	29.91	29.000	-0.908	-0.761	31.000	1.092	0.915	30.000	0.092	0.077	31.000	1.092	0.915	29.000	-0.908	-0.761	30.000	0.092	0.077				**-0.361**	**0.635**	**0.137**
20	19.96	20.000	0.038	0.032	21.000	1.038	0.870	18.000	-1.962	-1.644	21.000	1.038	0.870	18.000	-1.962	-1.644	20.000	0.038	0.032				**-0.814**	**0.590**	**-0.112**
10	10.02	10.000	-0.016	-0.013	10.000	-0.016	-0.013	9.000	-1.016	-0.851	11.000	0.984	0.825	9.000	-1.016	-0.851	12.000	1.984	1.662				**-0.429**	**0.825**	**0.198**
0	0.07				1.000	0.931	0.780	0.000	-0.069	-0.058	1.000	0.931	0.780	0.000	-0.069	-0.058	0.000	-0.069	-0.058	-1.000	-1.069	-0.896	**-0.253**	**0.500**	**0.124**
-10	-9.88				-10.000	-0.123	-0.103	-11.000	-1.123	-0.941	-10.000	-0.123	-0.103	-11.000	-1.123	-0.941	-11.000	-1.123	-0.941	-10.000	-0.123	-0.103	**-0.496**	**-0.382**	**-0.439**
-20	-19.82				-20.000	-0.177	-0.148	-20.000	-0.177	-0.148	-20.000	-0.177	-0.148	-20.000	-0.177	-0.148	-19.000	0.823	0.690	-20.000	-0.177	-0.148	**-0.111**	**0.131**	**0.010**
-30	-29.77				-30.000	-0.230	-0.193	-30.000	-0.230	-0.193	-29.000	0.770	0.645	-30.000	-0.230	-0.193	-29.000	0.770	0.645	-31.000	-1.230	-1.031	**-0.354**	**0.366**	**0.006**
-40	-39.72				-40.000	-0.284	-0.238	-40.000	-0.284	-0.238	-40.000	-0.284	-0.238	-40.000	-0.284	-0.238	-38.000	1.716	1.438	-40.000	-0.284	-0.238	**-0.178**	**0.321**	**0.071**
-50	-49.66				-50.000	-0.338	-0.283	-51.000	-1.338	-1.121	-50.000	-0.338	-0.283	-50.000	-0.338	-0.283	-48.000	1.662	1.393	-50.000	-0.338	-0.283	**-0.422**	**0.276**	**-0.073**
-60	-59.61				-60.000	-0.391	-0.328				-59.000	0.609	0.510				-59.000	0.609	0.510				**0.000**	**0.231**	**0.115**

Full Scale = -59.610 to 59.750 = 119.356

Linearity = (0.825/119.36)*100 = 0.691 %

Repeat. = (1.676/119.36)*100 = 1.404 %

Meas. Acc = -0.814 to 0.825 %

Hysteresis = (2.513/119.36)*100 = 2.105 %

RangeTrack Goniometer Calibration Tables

		Up			Down			Up			Down			Up			Down			Up					
Measurand	**Predicted (Regr.)**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Up Avg Er**	**Down Avg Er**	**Avg Error**
10.0	10.29				10.000	-0.291	-0.243				10.000	-0.291	-0.243				10.000	-0.291	-0.243				**0.000**	**-0.243**	**-0.121**
30.0	30.31				30.000	-0.305	-0.254	30.000	-0.305	-0.254	29.000	-1.305	-1.087	30.000	-0.305	-0.254	30.000	-0.305	-0.254	29.000	-1.305	-1.087	**-0.532**	**-0.532**	**-0.532**
50.0	50.32				50.000	-0.320	-0.266	49.000	-1.320	-1.099	50.000	-0.320	-0.266	50.000	-0.320	-0.266	49.000	-1.320	-1.099	50.000	-0.320	-0.266	**-0.544**	**-0.544**	**-0.544**
70.0	70.33	70.000	-0.334	-0.278	69.000	-1.334	-1.110	69.000	-1.334	-1.110	69.000	-1.334	-1.110	69.000	-1.334	-1.110	70.000	-0.334	-0.278	70.000	-0.334	-0.278	**-0.694**	**-0.833**	**-0.764**
90.0	90.35	90.000	-0.348	-0.289	89.000	-1.348	-1.122	90.000	-0.348	-0.289	89.000	-1.348	-1.122	90.000	-0.348	-0.289	90.000	-0.348	-0.289				**-0.217**	**-0.845**	**-0.531**
110.0	110.36	110.000	-0.362	-0.301	110.000	-0.362	-0.301	110.000	-0.362	-0.301	110.000	-0.362	-0.301	110.000	-0.362	-0.301	110.000	-0.362	-0.301				**-0.226**	**-0.301**	**-0.264**
130.0	130.38	129.000	-1.376	-1.146				129.000	-1.376	-1.146				130.000	-0.376	-0.313							**-0.651**	**0.000**	**-0.326**

Full Scale = 130.38-10.29= 120.090

Linearity = 0.215/120.090*100 = -0.442 %

Repeat. = (0.455- 0.010)/120.090*100 = 0.693 %

Meas. Acc = -0.656 to 0.493 %

October 23rd 2004		Up			Down			Up			Down			Up			Down			Up					
Measurand	**Predicted (Regr.)**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Obs**	**Er**	**% Er**	**Up Avg Er**	**Down Avg Er**	**Avg Error**
0	-1.025				0	1.025	0.641				0	1.025	0.641				0	1.025	0.641				**0.000**	**0.641**	**0.321**
20	18.945				19	0.055	0.034	19	0.055	0.034	19	0.055	0.034	19	0.055	0.034	21	2.055	1.286	19	0.055	0.034	**0.034**	**0.452**	**0.243**
40	38.915				38	-0.915	-0.573	39	0.085	0.053	39	0.085	0.053	38	-0.915	-0.573	39	0.085	0.053	39	0.085	0.053	**-0.155**	**-0.155**	**-0.155**
60	58.884				58	-0.884	-0.554	58	-0.884	-0.554	58	-0.884	-0.554	58	-0.884	-0.554	58	-0.884	-0.554	59	0.116	0.072	**-0.259**	**-0.554**	**-0.406**
80	78.854	79	0.146	0.091	78	-0.854	-0.535	79	0.146	0.091	78	-0.854	-0.535	78	-0.854	-0.535	78	-0.854	-0.535				**-0.088**	**-0.535**	**-0.311**
100	98.824	99	0.176	0.110	99	0.176	0.110	98	-0.824	-0.516	98	-0.824	-0.516	99	0.176	0.110	99	0.176	0.110				**-0.074**	**-0.098**	**-0.086**
120	118.794	119	0.206	0.129	119	0.206	0.129	119	0.206	0.129	119	0.206	0.129	119	0.206	0.129	119	0.206	0.129				**0.097**	**0.129**	**0.113**
140	138.763	139	0.237	0.148	139	0.237	0.148	140	1.237	0.774	139	0.237	0.148	139	0.237	0.148	139	0.237	0.148				**0.268**	**0.148**	**0.208**
160	158.733	159	0.267	0.167				159	0.267	0.167				159	0.267	0.167							**0.125**	**0.000**	**0.063**

Full Scale = 158.732 to -1.025 = 159.758

Linearity = (0.641/159.76)*100 = 0.401 %

Repeat. = (-1.252/159.76)*100 = -0.784 %

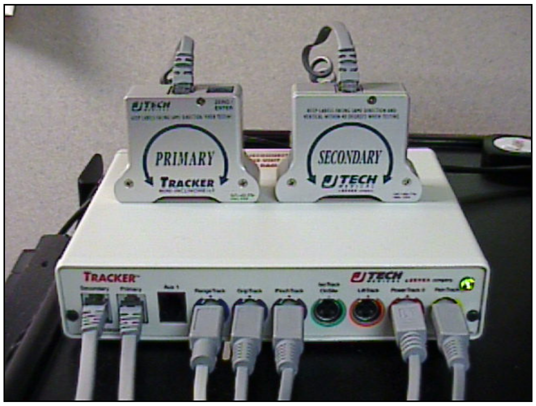
Meas. Acc = -0.554 to 0.641 %

Hysteresis = (-1.252/159.76)*100 = -0.784 %

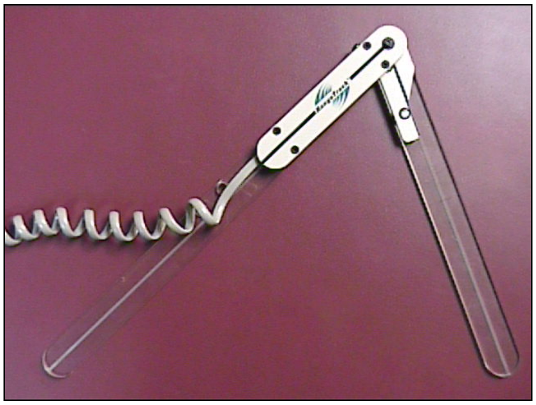
APPENDIX G

Photographs

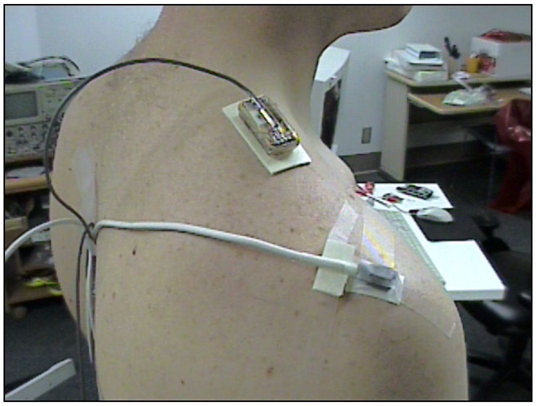
1. JTECH Medical Tracker *Dualer*™ dual digital inclinometers.



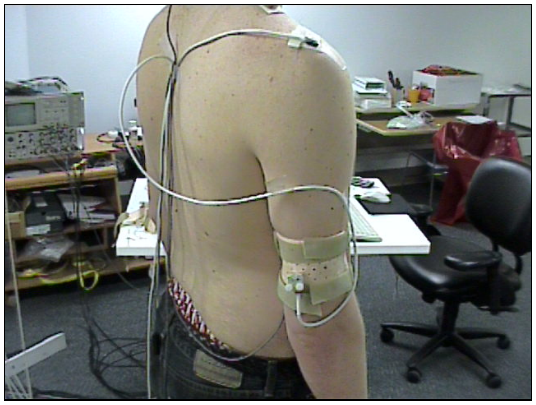
2. JTECH Medical Tracker *RangeTrack*™ digital goniometer.



3. Upper trapezius EMG and scapula kinematic sensors.

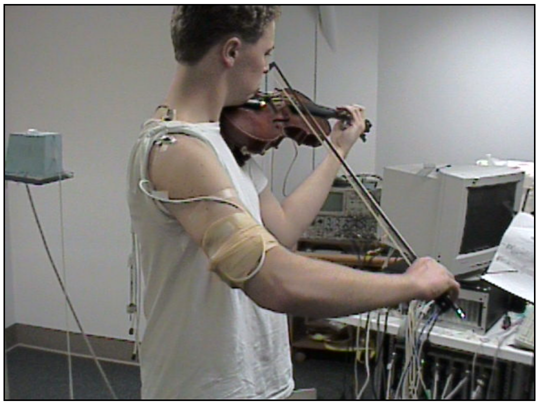


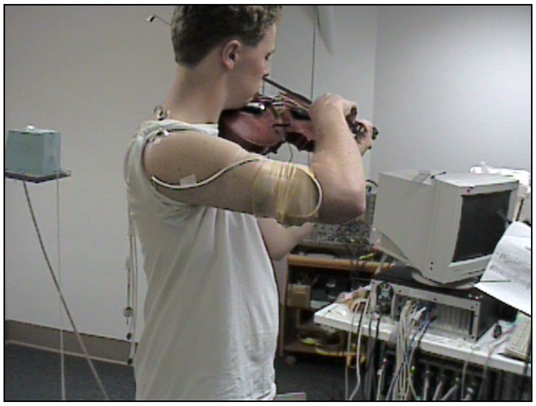
4. Participant showing scapula and arm kinematic sensors.



5. Participant playing on middle (A and D) strings.

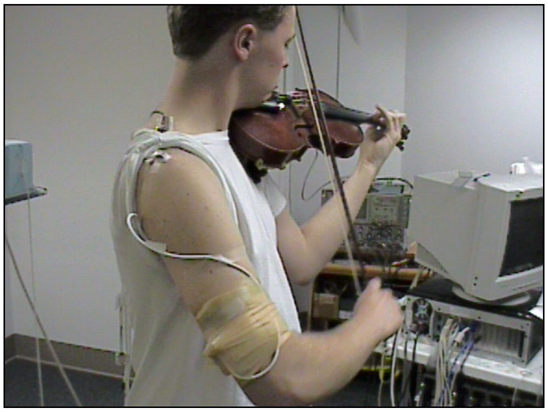
6. Participant playing on the bass (G) string.

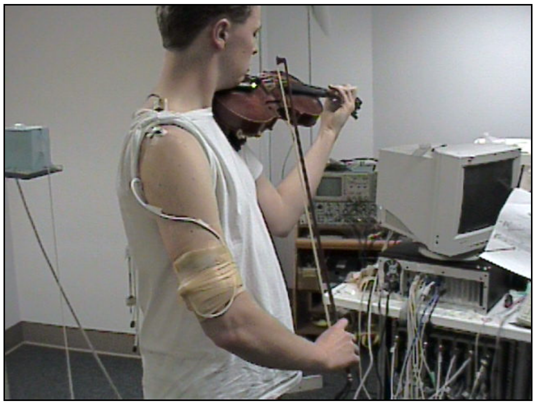




7. Participant playing on the E-String.

8. Participant playing on the E-String.





APPENDIX H

Miscellaneous Analyses

Additional Demographic Information

Table H.1. Musical Experience by Group. Data are presented as means and standard errors, and p-values reflect results of Student's t-tests.

Music Experience		Injured (n=20) Mean (SE)	Uninjured (n=30) Mean (SE)	p-value
Experience (years)		36.0 (3.5)	29.0 (2.7)	0.116
Practice Time (hrs/week)		10.3 (2.5)	11.4 (1.7)	0.702
Performance Time (hrs/week)		6.0 (2.4)	3.5 (0.9)	0.260
Teaching Time (hrs/week)		7.2 (2.5)	5.2 (1.5)	0.455
Orchestra	Professional (n)	16 (80.0)	8 (26.7)	0.001*
	Amateur (n)	2 (10.0)	14 (46.7)	0.001*
	Student (n)	2 (10.0)	8 (26.7)	0.001*

Table H.2. Medical History by Group. Data are presented as number of cases reported and standard errors, and p-values reflect results of Student’s t-tests.

Medical History	Injured (n=20) Mean % (SE)	Uninjured (n=30) Mean (SE)	p-value
Tobacco Use	1 (5.0)	1 (3.3)	0.771
Alcohol Use	14 (70.0)	22 (73.3)	0.780
Beta Blocker Use	8 (40.0)	7 (23.3)	0.212
Arthritis	4 (20.0)	2 (6.7)	0.160
Thyroid	1 (5.0)	1 (3.3)	0.771
Tendinitis	6 (30.0)	7 (23.3)	0.602
DeQuervain’s Tenosynovitis	0 (0.0)	1 (3.3)	0.414
Carpal Tunnel Syndrome	1 (5.0)	0 (0.0)	0.221
Thoracic Outlet Syndrome	2 (10.0)	0 (0.0)	0.080
Cubital Tunnel Syndrome	0 (0.0)	0 (0.0)	-
Neurological Disorders	1 (5.0)	0 (0.0)	0.221
Lateral Epicondylitis	4 (20.0)	3 (10.0)	0.323
Medial Epicondylitis	0 (0.0)	0 (0.0)	-

Table H.3. Scapula Tilting EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (degrees)	**<1**	**1-3**	**>3**	**Amplitude Total**
>0.5	1.9	5.7	12.1	19.7
-7.6 to 0.5	3.6	11.7	27.2	42.5
< -7.6	2.5	3.8	31.4	37.8
Time Period Total	8.1	21.2	70.7	100.0

Uninjured Fast

Amplitude (degrees)	**<1**	**1-3**	**>3**	**Amplitude Total**
>0.5	5.0	4.7	15.2	24.8
-7.6 to 0.5	9.9	16.4	16.2	42.5
< -7.6	3.0	6.3	23.3	32.7
Time Period Total	18.0	27.3	54.7	100.0

Injured Slow

Amplitude (degrees)	**<1**	**1-3**	**>3**	**Amplitude Total**
>0.5	1.5	4.4	23.9	29.8
-7.6 to 0.5	3.7	8.9	28.6	41.2
< -7.6	2.4	4.1	22.6	29.0
Time Period Total	7.6	17.4	75.0	100.0

Injured Fast

		Injured	**Fast**	
Amplitude (degrees)	**<1**	**1-3**	**>3**	**Amplitude Total**
>0.5	6.9	4.7	23.7	35.3
-7.6 to 0.5	10.2	11.2	18.3	39.7
< -7.6	3.5	4.2	17.3	25.0
Time Period Total	20.5	20.1	59.4	100.0

Table H.4. Scapula Upward Rotation EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> -1	2.0	3.6	21.2	26.8
-14 to -1	3.7	12.2	26.2	42.1
< -14	2.2	9.3	19.6	31.1
Time Period Total	7.9	25.2	66.9	100.0

Uninjured Fast

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> -1	5.3	4.4	16.9	26.6
-14 to -1	16.3	19.6	10.4	46.3
< -14	9.7	5.7	11.6	27.1
Time Period Total	31.4	29.7	38.9	100.0

Injured Slow

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> -1	2.8	8.1	12.3	23.2
-14 to -1	4.3	15.5	28.4	48.2
< -14	1.7	8.0	18.8	28.6
Time Period Total	8.9	31.6	59.6	100.0

Injured Fast

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> -1	11.7	3.6	9.1	24.3
-14 to -1	23.2	17.9	7.4	48.5
< -14	10.0	7.4	9.7	27.2
Time Period Total	44.9	28.9	26.2	100.0

Table H.5. Scapula Internal/External Rotation EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (degrees)	Time period (s) <1	1-3	>3	Amplitude Total
> 45.3	3.4	3.7	11.6	18.7
34 to 45.3	3.6	14.2	34.1	52.0
< 34	1.2	6.0	22.1	29.3
Time Period Total	8.3	24.0	67.8	100.0

Uninjured Fast

Amplitude (degrees)	Time period (s) <1	1-3	>3	Amplitude Total
> 45.3	5.6	3.2	11.0	19.8
34 to 45.3	10.5	11.8	29.0	51.3
< 34	4.0	3.0	21.9	28.9
Time Period Total	20.1	18.0	61.9	100.0

Injured Slow

Amplitude (degrees)	Time period (s) <1	1-3	>3	Amplitude Total
> 45.3	4.7	8.0	21.6	34.3
34 to 45.3	5.4	20.2	12.8	38.4
< 34	2.0	8.1	17.2	27.3
Time Period Total	12.1	36.3	51.6	100.0

Injured Fast

Amplitude (degrees)	Time period (s) <1	1-3	>3	Amplitude Total
> 45.3	8.3	5.7	19.3	33.3
34 to 45.3	11.9	7.9	17.3	37.0
< 34	3.7	3.0	23.1	29.7
Time Period Total	23.8	16.5	59.7	100.0

Table H.6. Glenohumeral Flexion EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 23.9	7.9	13.4	11.3	32.6
8.2 to 23.9	12.9	22.6	7.7	43.2
< 8.2	3.8	14.1	6.3	24.2
Time Period Total	24.5	50.1	25.3	100.0

Uninjured Fast

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 23.9	7.2	1.9	7.3	16.4
8.2 to 23.9	23.6	14.7	6.7	45.0
< 8.2	11.6	7.7	19.3	38.6
Time Period Total	42.4	24.3	33.3	100.0

Injured Slow

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 23.9	6.7	6.7	6.4	19.8
8.2 to 23.9	13.8	18.6	3.3	35.8
< 8.2	3.7	23.3	17.4	44.4
Time Period Total	24.3	48.7	27.1	100.0

Injured Fast

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 23.9	6.2	2.1	5.0	13.3
8.2 to 23.9	19.4	13.1	2.4	34.8
< 8.2	8.5	5.9	37.5	51.9
Time Period Total	34.1	21.1	44.9	100.0

Table H.7. Glenohumeral Abduction EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (degrees)	Time period (s)			
	<1	1-3	>3	Amplitude Total
< -57.2	3.3	6.2	17.5	27.0
-57.2 to -40.5	7.5	19.2	12.3	39.0
> -40.5	2.7	10.5	20.7	34.0
Time Period Total	13.5	36.0	50.5	100.0

Uninjured Fast

Amplitude (degrees)	Time period (s)			
	<1	1-3	>3	Amplitude Total
> -40.5	15.8	11.7	6.1	33.5
-57.2 to -40.5	36.0	5.9	0.0	41.9
< -57.2	16.5	8.0	0.0	24.6
Time Period Total	68.3	25.6	6.1	100.0

Injured Slow

Amplitude (degrees)	Time period (s)			
	<1	1-3	>3	Amplitude Total
> -40.5	4.3	7.2	10.6	22.1
-57.2 to -40.5	8.9	24.1	9.7	42.7
< -57.2	3.3	15.8	16.2	35.3
Time Period Total	16.4	47.1	36.5	100.0

Injured Fast

Amplitude (degrees)	Time period (s)			
	<1	1-3	>3	Amplitude Total
> -40.5	17.7	10.0	1.0	28.7
-57.2 to -40.5	39.9	5.9	0.0	45.8
< -57.2	19.3	5.0	1.2	25.5
Time Period Total	76.8	20.9	2.2	100.0

Table H.8. Glenohumeral Internal/External Rotation EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 4.9	4.2	7.1	12.2	23.5
-10.7 to 4.9	11.4	17.0	9.9	38.4
< -10.7	4.9	14.0	19.2	38.2
Time Period Total	20.6	38.2	41.3	100.0

Uninjured Fast

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 4.9	15.7	8.5	3.5	27.7
-10.7 to 4.9	40.0	3.0	0.0	43.0
< -10.7	25.5	3.8	0.0	29.3
Time Period Total	81.3	15.2	3.5	100.0

Injured Slow

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 4.9	3.0	5.0	26.2	34.2
-10.7 to 4.9	9.1	13.2	6.7	29.1
< -10.7	3.8	10.4	22.5	36.7
Time Period Total	15.9	28.6	55.5	100.0

Injured Fast

Amplitude (degrees)	<1	1-3	>3	Amplitude Total
> 4.9	4.1	3.0	29.7	36.8
-10.7 to 4.9	23.7	6.8	0.8	31.3
< -10.7	12.5	4.4	15.0	31.9
Time Period Total	40.2	14.3	45.5	100.0

Table H.9. Upper Trapezius EMG EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	17.1	11.2	17	45.3
50-100	24.5	11.1	1.6	37.2
<50	9.5	5.2	2.9	17.6
Time Period Total	51.1	27.5	21.5	100.1

Uninjured Fast

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	22	19.8	13.2	55
50-100	25.3	2.9	0	28.2
<50	14.3	2.4	0.1	16.8
Time Period Total	61.6	25.1	13.3	100

Injured Slow

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	17.5	11.2	20.6	49.3
50-100	24.3	5.9	0.4	30.6
<50	13.3	3.6	3.2	20.1
Time Period Total	37.6	20.7	24.2	100

Injured Fast

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	25.2	20.2	3.8	49.2
50-100	28.4	2.9	0	31.3
<50	16.3	2.9	0.4	19.6
Time Period Total	69.9	26	4.2	100.1

Table H.10. Serratus Anterior EMG EVA data for Slow and Fast trials for Injured and Uninjured participants. Contents of the table (in blocks) represent percentages of time spent at an amplitude level (vertical axis) for a time period (horizontal axis). Margin totals are presented in parentheses.

Uninjured Slow

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	13.1	10.4	20	43.5
50-100	21.8	11.5	1.4	34.7
<50	8.5	5.4	8.1	22
Time Period Total	43.4	27.3	29.5	100.2

Uninjured Fast

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	25.2	20.2	19.9	65.3
50-100	21.8	1.4	0	23.2
<50	10.6	0.9	0	11.5
Time Period Total	57.6	22.5	19.9	100

Injured Slow

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	11.8	13.7	14	39.5
50-100	24.3	11.7	0.8	36.8
<50	13.1	6.1	4.5	23.7
Time Period Total	37.4	31.5	19.3	100

Injured Fast

Amplitude (%RVE)	<0.3	0.3-1	>1	Amplitude Total
>100	23.8	26.1	11.9	61.8
50-100	23.6	1.1	0	24.7
<50	12.4	1.1	0	13.5
Time Period Total	59.8	28.3	11.9	100

Table H.11.Comparison of Scapula Tilting resting position as measured using the Flock-of-Birds three-dimensional kinematic system (horizontal axis) and as observed during physical examination (vertical axis) using Fisher's Exact Test.

	Flock-of-Birds Measurement		**Total**
Observed Alignment	**Median > -11^o n (%)**	**Median <= -11^o n (%)**	
Normal Alignment	20 (47.6)	5 (62.5)	**25**
Anterior Tipping	22 (52.4)	3 (37.5)	**25**
Total	**42**	**8**	**50**

Two-Sided probability <=p: 0.702

Table H.12. Comparison of Scapula Upward Rotation resting position as measured using the Flock-of-Birds three-dimensional kinematic system (horizontal axis) and as observed during physical examination (vertical axis) using Fisher's Exact Test.

	Flock-of-Birds Measurement		**Total**
Observed Alignment	**Median <=32^o n (%)**	**Median >32^o n (%)**	
Normal Alignment	7 (58.3)	25 (65.8)	**32**
Upward Rotation	5 (41.7)	13 (34.2)	**18**
Total	**12**	**38**	**50**

Two-Sided probability <=p: 0.735

Table H.13. Comparison of Scapula Internal/External Rotation resting position as measured using the Flock-of-Birds three-dimensional kinematic system (horizontal axis) and as observed during physical examination (vertical axis) using Fisher's Exact Test.

	Flock-of-Birds Measurement		**Total**
Observed Alignment	**Median <=-2^o n (%)**	**Median >-2^o n (%)**	
Normal Alignment	15 (39.5)	2 (16.7)	**17**
Internal/External Rotation	23 (60.5)	10 (83.3)	**33**
Total	**38**	**12**	**50**

Two-Sided probability <=p: 0.181

Table H.14. Pearson Correlation Coefficients for Arm Elevation between 50 and 65^o for uninjured participants performing slow repertoire

Uninjured **Slow Performance** Pearson Correlation Coefficient (p-Value)	**Scapula Internal/External Rotation**	**Scapula Upward Rotation**	**Scapula Tilting**	**GHJ Abduction**	**GHJ Flexion**	**GHJ Internal/External Rotation**	**Serratus Anterior**	**Upper Trapezius**	**Age**	**Arm Plane Elevation**	**Gender**
Scapula Internal/External Rotation	-	-0.145 (0.413)	-0.287 (0.099)	-0.010 (0.955)	-0.496 (0.003)	-0.318 (0.067)	-0.158 (0.379)	-0.112 (0.527)	0.178 (0.315)	0.090 (0.614)	0.022 (0.902)
Scapula Upward Rotation		-	0.023 (0.899)	-0.922 (<0.001)	0.046 (0.796)	-0.147 (0.406)	-0.159 (0.377)	0.199 (0.258)	-0.029 (0.873)	-0.048 (0.787)	-0.299 (0.086)
Scapula Tilting			-	0.144 (0.416)	0.017 (0.924)	-0.005 (0.976)	0.062 (0.730)	-0.197 (0.265)	-0.048 (0.787)	0.292 (0.095)	-0.165 (0.352)
GHJ Abduction				-	0.077 (0.665)	0.106 (0.549)	0.125 (0.488)	-0.205 (0.245)	0.068 (0.702)	0.155 (0.383)	0.209 (0.235)
GHJ Flexion					-	-0.020 (0.912)	0.151 (0.401)	0.109 (0.541)	-0.282 (0.107)	0.714 (<0.001)	-0.279 (0.110)
GHJ Internal/External Rotation						-	-0.064 (0.724)	-0.299 (0.086)	-0.185 (0.294)	-0.242 (0.168)	0.145 (0.414)
Serratus Anterior							-	-0.064 (0.724)	-0.299 (0.086)	-0.185 (0.293)	-0.242 (0.168)
Upper Trapezius								-	0.016 (0.928)	-0.076 (0.671)	0.109 (0.540)
Age									-	-0.186 (0.291)	-0.130 (0.465)
Arm Plane Elevation										-	-0.383 (0.026)
Gender											-

Table H.15. Pearson Correlation Coefficients for Arm Elevation between 50 and 65^{o} for uninjured participants performing fast repertoire

Uninjured Fast Performance Pearson Correlation Coefficient (p-Value)	**Scapula Internal/External Rotation**	**Scapula Upward Rotation**	**Scapula Tilting**	**GHJ Abduction**	**GHJ Flexion**	**GHJ Internal/External Rotation**	**Serratus Anterior**	**Upper Trapezius**	**Age**	**Arm Plane Elevation**	**Gender**
Scapula Internal/External Rotation	-	-0.197 (0.264)	-0.392 (0.022)	0.029 (0.871)	-0.566 (0.001)	-0.301 (0.083)	-0.098 (0.586)	-0.093 (0.560)	0.166 (0.349)	-0.115 (0.518)	0.104 (0.558)
Scapula Upward Rotation		-	0.073 (0.684)	-0.923 (<0.001)	0.084 (0.637)	-0.196 (0.268)	-0.140 (0.438)	-0.124 (0.485)	-0.013 (0.943)	-0.026 (0.884)	-0.339 (0.050)
Scapula Tilting			-	0.090 (0.611)	0.027 (0.878)	0.006 (0.971)	0.014 (0.937)	-0.244 (0.164)	-0.026 (0.885)	0.250 (0.153)	-0.101 (0.569)
GHJ Abduction				-	0.091 (0.610)	0.141 (0.428)	0.120 (0.506)	0.135 (0.446)	0.022 (0.903)	0.200 (0.256)	0.242 (0.169)
GHJ Flexion					-	-0.036 (0.841)	0.064 (0.725)	0.148 (0.402)	-0.225 (0.202)	0.785 (<0.001)	-0.268 (0.125)
GHJ Internal/External Rotation						-	0.042 (0.816)	-0.436 (0.807)	-0.178 (0.313)	-0.258 (0.140)	0.131 (0.460)
Serratus Anterior							-	0.331 (0.060)	-0.014 (0.939)	-0.003 (0.988)	0.378 (0.030)
Upper Trapezius								-	-0.057 (0.751)	-0.051 (0.777)	0.169 (0.339)
Age									-	-0.147 (0.408)	-0.130 (0.465)
Arm Plane Elevation										-	-0.308 (0.076)
Gender											-

Table H.16. Pearson Correlation Coefficients for Arm Elevation between 50 and 65^{o} for injured participants performing slow repertoire

Injured **Slow Performance** Pearson Correlation Coefficient (p-Value)	**Scapula Internal/External Rotation**	**Scapula Upward Rotation**	**Scapula Tilting**	**GHJ Abduction**	**GHJ Flexion**	**GHJ Internal/External Rotation**	**Serratus Anterior**	**Upper Trapezius**	**Age**	**Arm Plane Elevation**	**Gender**
Scapula Internal/External Rotation	-	-0.022 (0.925)	0.135 (0.570)	0.062 (0.795)	-0.542 (0.014)	0.090 (0.705)	0.133 (0.606)	-0.038 (0.873)	0.275 (0.240)	0.352 (0.128)	0.155 (0.514)
Scapula Upward Rotation		-	0.326 (0.161)	-0.939 (<0.001)	-0.084 (0.724)	0.183 (0.439)	-0.591 (0.006)	-0.490 (0.028)	-0.306 (0.190)	0.148 (0.533)	-0.299 (0.200)
Scapula Tilting			-	-0.116 (0.626)	-0.552 (0.012)	0.006 (0.981)	-0.231 (0.326)	-0.034 (0.887)	-0.410 (0.073	0.170 (0.474)	-0.149 (0.531)
GHJ Abduction				-	0.039 (0.870)	-0.259 (0.271)	0.536 (0.015)	0.544 (0.013)	0.195 (0.410)	-0.002 (0.993)	0.271 (0.247)
GHJ Flexion					-	-0.144 (0.544)	0.000 (0.999)	-0.096 (0.688)	-0.029 (0.904)	0.386 (0.093)	-0.129 (0.588)
GHJ Internal/External Rotation						-	-0.215 (0.362)	-0.078 (0.744)	0.019 (0.937)	-0.093 (0.696)	-0.127 (0.594)
Serratus Anterior							-	-0.013 (0.957)	0.505 (0.023)	-0.092 (0.700)	0.696 (0.001)
Upper Trapezius								-	-0.367 (0.111)	-0.212 (0.369)	-0.121 (0.611)
Age									-	-0.085 (0.722)	0.567 (0.009)
Arm Plane Elevation										-	-0.157 (0.510)
Gender											-

Table H.17. Pearson Correlation Coefficients for Arm Elevation between 50 and 65^o for injured participants performing fast repertoire

Injured **Fast Performance** Pearson Correlation Coefficient (p-Value)	**Scapula Internal/External Rotation**	**Scapula Upward Rotation**	**Scapula Tilting**	**GHJ Abduction**	**GHJ Flexion**	**GHJ Internal/External Rotation**	**Serratus Anterior**	**Upper Trapezius**	**Age**	**Arm Plane Elevation**	**Gender**
Scapula Internal/External Rotation	-	0.116 (*0.626)	0.130 (0.584)	-0.060 (0.802)	-0.527 (0.008)	0.136 (0.567)	0.006 (0.979)	-0.125 (0.599)	0.285 (0.224)	0.281 (0.231)	0.121 (0.612)
Scapula Upward Rotation		-	0.343 (0.138)	-0.943 (<0.001)	-0.083 (0.729)	0.008 (0.973)	-0.570 (0.009)	-0.488 (0.029)	-0.289 (0.216)	0.283 (0.226)	-0.296 (0.205)
Scapula Tilting			-	-0.236 (0.316)	-0.562 (0.010)	0.020 (0.934)	-0.295 (0.207)	-0.176 (0.457)	-0.331 (0.154)	0.089 (0.708)	-0.129 (0.588)
GHJ Abduction				-	0.023 (0.922)	-0.105 (0.660)	0.516 (0.020)	0.546 (0.013)	0.227 (0.335)	-0.222 (0.347)	0.288 (0.218)
GHJ Flexion					-	-0.161 (0.497)	0.073 (0.760)	-0.123 (0.605)	-0.003 (0.992)	0.441 (0.052)	-0.154 (0.517)
GHJ Internal/External Rotation						-	-0.013 (0.957)	-0.041 (0.883)	0.046 (0.846)	-0.084 (0.725)	-0.092 (0.699)
Serratus Anterior							-	-0.062 (0.798)	0.465 (0.039)	-0.126 (0.597)	0.505 (0.023)
Upper Trapezius								-	-0.397 (0.083)	-0.463 (0.040)	-0.159 (0.503)
Age									-	0.047 (0.844)	0.567 (0.009)
Arm Plane Elevation										-	-0.203 (0.392)
Gender											-

Table H.18. Arm Elevation between 50^o and 65^o descriptive statistics for the uninjured group

Dependent Variable	**Speed**	**n**	**Mean** Deg. volts	**Std. Dev.** Deg. volts	**Minimum** Deg. volts	**Maximum** Deg. volts
Scapula Tilting	Slow	30	-4.61	7.15	-21.04	11.00
	Fast	30	-3.75	7.34	-16.49	12.69
Scapula Upward Rotation	Slow	30	-6.92	10.34	-31.25	13.79
	Fast	30	-7.55	10.88	-34.90	13.27
Scapula Internal/External Rotation	Slow	30	37.91	9.36	15.90	64.03
	Fast	30	38.86	9.43	20.08	65.40
Glenohumeral Flexion	Slow	30	17.30	10.93	-10.49	39.05
	Fast	30	12.55	11.45	-9.10	38.76
Glenohumeral abduction	Slow	30	-48.75	10.87	-66.57	-25.20
	Fast	30	-48.15	10.98	-67.86	-22.71
Glenohumeral Internal/External Rotation	Slow	30	-2.85	16.96	-22.71	65.27
	Fast	30	-2.04	16.68	-20.50	67.47
Upper Trapezius	Slow	30	1.06	0.44	0.40	2.07
	Fast	30	1.31	0.64	0.42	2.91
Serratus Anterior	Slow	29	1.10	0.68	0.37	3.26
	Fast	29	1.92	1.70	0.52	9.75

Table H.19. Arm Elevation between 50^o and 65^o descriptive statistics for the injured group

Dependent Variable	**Speed**	**n**	**Mean** Deg. volts	**Std. Dev.** Deg. volts	**Minimum** Deg. volts	**Maximum** Deg. volts
Scapula Tilting	Slow	20	-2.24	10.91	-19.32	29.53
	Fast	20	-1.83	10.53	-21.01	28.94
Scapula Upward Rotation	Slow	20	-7.45	7.69	-20.67	7.14
	Fast	20	-7.98	7.25	-19.54	3.18
Scapula Internal/External Rotation	Slow	20	39.71	10.02	17.35	54.64
	Fast	20	40.20	10.32	18.70	57.33
Glenohumeral Flexion	Slow	20	10.97	11.68	-9.44	37.06
	Fast	20	7.38	12.58	-15.25	35.07
Glenohumeral abduction	Slow	20	-49.60	6.78	-59.88	-36.76
	Fast	20	-49.28	7.08	-61.05	-35.69
Glenohumeral Internal/External Rotation	Slow	20	1.18	28.75	-49.17	74.47
	Fast	20	2.60	30.33	-47.69	80.74
Upper Trapezius	Slow	20	1.48	1.68	0.38	8.19
	Fast	20	1.48	1.61	0.43	8.04
Serratus Anterior	Slow	20	1.14	0.87	0.38	4.12
	Fast	20	1.68	1.04	0.63	4.61

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