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3D movement and muscle activity patterns in a violin bowing task

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**A thesis submitted for completion of the requirements for the degree of
Master of Science in Applied Health Sciences**

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ABSTRACT

Objective: Overuse injuries in violinists are a problem that has been primarily analyzed through the use of questionnaires. Simultaneous 3D motion analysis and EMG to measure muscle activity has been suggested as a quantitative technique to explore this problem by identifying movement patterns and muscular demands which may predispose violinists to overuse injuries. This multi-disciplinary analysis technique has, so far, had limited use in the music world. The purpose of this study was to use it to characterize the demands of a violin bowing task.

Subjects: Twelve injury-free violinists volunteered for the study. The subjects were assigned to a novice or expert group based on playing experience, as determined by questionnaire.

Design and Settings: Muscle activity and movement patterns were assessed while violinists played five bowing cycles (one bowing cycle = one down-bow + one up-bow) on each string (G, D, A, E), at a pulse of 4 beats per bow and 100 beats per minute.

Measurements: An upper extremity model created using coordinate data from markers placed on the right acromion process, lateral epicondyle of the humerus and ulnar styloid was used to determine minimum and maximum joint angles, ranges of motion (ROM) and angular velocities at the shoulder and elbow of the bowing arm. Muscle activity in right anterior deltoid, biceps brachii and triceps brachii was assessed during maximal voluntary contractions (MVC) and during the playing task. Data were analysed for significant differences across the strings and between experience groups.

Results: Elbow flexion/extension ROM was similar across strings for both groups. Shoulder flexion/extension ROM increased as the bow moved across the strings and was

larger for the experts. Angular velocity changes mirrored changes in ROM. Deltoid was the most active of the muscles assessed (20% MVC) and displayed a pattern of constant activation to maintain shoulder abduction. Biceps and triceps were less active (4 – 12% MVC) and showed a more periodic ‘on and off’ pattern. Novices’ muscle activity was higher in all cases. Experts’ muscle activity showed a consistent pattern across strings, whereas the novices were more irregular. The agonist-antagonist roles of biceps and triceps during the bowing motion were clearly defined in the expert group, but not as apparent in the novice group.

Conclusions: Bowing movement appears to be controlled by the shoulder rather than the elbow as shoulder ROM changed across strings while elbow ROM remained the same. Shoulder injuries are probably due to repetition as the muscle activity required for the movement is small. Experts require a smaller amount of muscle activity to perform the movement, possibly due to more efficient muscle activation patterns as a result of practice. This quantitative multidisciplinary approach to analysing violinists’ movements can contribute to fuller understanding of both playing demands and injury mechanisms.

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CHAPTER 1: INTRODUCTION

Musicians are subject to a variety of soft-tissue and repetitive strain injuries as a result of the postures, practice and performance techniques associated with their chosen vocation.

In the United States, roughly 130,000 instrumentalists make a living from performing (Lockwood, 1989). In a review of studies dealing with the incidence and prevalence of playing related injuries in musicians, Zaza (1998) found that between 39% and 87% of musicians reported an injury due to playing. In orchestras the incidence of injury was shown to be 50% (Fry, 1986). String players have the greatest incidence of injury (Berque & Gray, 2002; Heming, 2004; Larsson, Baum, Mudholkar & Kollia, 1993; Levy, Lee, Brandfonbrener, Press, & Levy, 1992; Tulchinsky & Riolo, 1994; Turner-Stokes & Reid, 1999; Zaza & Farewell, 1997) with 73% to 75% reporting an injury as a result of playing (Lockwood, 1989).

Injuries in musicians have been examined primarily through the use of questionnaires, and a very small number of clinical reports. It has been established that the injuries that musicians sustain are as numerous and debilitating as the better known work-related injuries, although not as widely recognized (Zaza, 1998). The main injuries that musicians are susceptible to are musculoskeletal disorders, more specifically, muscle-tendon overuse, acromiohumeral impingement, and shoulder instability (Knishkowsky & Lederman, 1986). There has been little research to systematically measure, in a quantitative way, the demands placed on muscles and joints when playing. Surface electromyography (EMG) and two dimensional (2D) or three dimensional (3D) motion analyses have been used separately to study violin technique. EMG has been used

to study muscle activity in injured and non injured musicians in a number of studies (Bejjani, Ferrara, & Pavlidis, 1989; Fagarasanu, Kumar & Narayan, 2004; Fjellman-Wiklund et al., 2004; Berque & Gray, 2002; Lederman, 2003; Levy et al., 1992; Philipson, Sorbye, Larson & Kaladjeu, 1990). Motion analysis has been used to assess musicians' movement in only a few studies using 2D analysis (Tulchinsky & Riolo, 1994) and 3D analysis (Turner-Stokes & Reid, 1999; Shan & Visentin, 2003). Recently, one study (Shan, Visentin & Schultz, 2004), combined both techniques to investigate further the kinematics and kinetics of playing the violin. Quantitative analysis of the playing motion allows a measurable assessment of the demands placed on muscle and joint tissues. This knowledge of tissue stress could then be used to better understand the development of overuse injuries. While data collected from questionnaires have been useful in identifying the incidence and prevalence of injuries in musicians, successful prevention and treatment will require the information that comes from quantitative analysis. Combining two quantitative assessment tools, such as EMG and motion analysis, allows a more detailed examination and understanding of the demands placed on violinists' muscles and joints.

This study was delimited to twelve injury free musicians who had played the violin for a minimum of two years. Subjects were assigned to the expert or novice group based on playing experience. Electromyography (EMG) from three muscles, and motion analysis characterized the violinists' muscle activity and movement patterns during a simple, repetitive bowing task. The purpose of the study was to assess simultaneously, using 3D motion analysis and EMG, muscle activity and movement patterns of the right upper extremity involved in violin bowing.

CHAPTER 2: REVIEW OF LITERATURE

Playing Demands

Instruments, played dynamically or held statically, put stress on musicians' bodies. In string players, especially violinists, the demands placed on the body are large. The violin, held with the left arm, is an average length of 38 cm from the top of the neck to the edge of the chin rest and the total weight ranges from 400 to 450 g (Jansson, 2002). The right arm controls a bow that weighs about 270 g (Szende & Nemessuri, 1971). The posture the violinist assumes when playing is stressful on the body in itself, even without holding the weight of the violin and bow for a period of time. Typically, playing posture requires a raised left shoulder, with the instrument supported in the left supraclavicular fossa. The head is rotated to the left and the neck is in a position of left lateral flexion. The left arm is abducted and externally rotated, and the left forearm is supinated. On the bowing arm, the right shoulder is dropped, internally rotated and abducted, and the forearm is pronated (Berque & Gray, 2002). When the demands of playing the violin are combined with the required body posture and weight of the instrument, the stresses placed on the body are greater than those needed to simply support the violin (Levy et al., 1992).

Playing Motion

There are specific movements, in both the hands and arms, which must occur when playing the violin, in order to achieve the proper tone, pitch, volume and quality of sound (Szende & Nemessuri, 1971). Shan and Visentin (2003) used 3D motion capture to provide a kinematic description of the right and left arm movement while playing. They

observed that the left arm, holding up the violin, was in a nearly static position (quasi-static) whereas the right arm, used to facilitate the bowing, was more dynamic. In the right arm there was a constant pattern of gross motor movement at the shoulder and elbow (greater motion occurring using larger muscle groups), while fine motor movement occurred at the wrist (slight movements using smaller muscle groups) and the resulting pattern was individualized (Shan & Visentin, 2003). The bowing motion, going from left to right during a down-bow, is not a parallel motion with respect to a plane of reference, rather it is angled diagonally downward (Szende & Nemessuri, 1971). This requires shoulder extension and abduction or adduction, and elbow extension during the downward motion. On the up-bow the opposite movements occur to raise the arm: shoulder flexion and adduction or abduction, and elbow flexion (Szende & Nemessuri, 1971; Tulchinsky & Riolo, 1994). The left arm remains in the starting position with the fingers flexed in order to depress the strings to achieve the correct accuracy and steady pressure needed to create the required sound (Szende & Nemessuri, 1971).

Muscles used for Control and Playing

To control the violin and the sounds being produced it is primarily muscles in the upper body which are active. The neck and shoulder muscles are most active when holding up the violin (Fry, 1986). The sternocleidomastoid is used during rotation and depression movement of the chin to support the violin (Levy et. al., 1992). On the left side of the body the trapezius is used to support and secure the violin, hold the head in place during playing, and is a stabilizer muscle for the constantly abducted left arm (Fjellman-Wiklund et al., 2004; Szende & Nemessuri, 1971). The left shoulder muscles,

particularly the anterior deltoid, are used to support the raised left arm (Szende & Nemessuri, 1971). In the left arm the biceps brachii is the principal muscle being used while playing as it facilitates and sustains supination and flexion of the elbow. The left triceps brachii acts antagonistically to the biceps brachii as it stabilizes and holds the partially extended position of the elbow. As no large extension movements occur in the left arm during playing, the triceps brachii is primarily used for defined technical tasks such as vibrato (which is a quick repeated increase and decrease in the frequency and pitch of a note) (Szende & Nemessuri, 1971). On the right side of the body, the trapezius muscle is responsible for facilitating the bowing motion (Fjellman-Wiklund et al., 2004; Szende & Nemessuri, 1971). The right shoulder muscles, such as the deltoid, have been described as being active during the constant movement of the right arm when playing. They have the greatest muscle activity when the shoulder is horizontally adducted and flexed at the beginning of a down-bow, especially at low speeds (Lockwood, 1989; Szende & Nemessuri, 1971; Shan, Visentin & Schultz, 2004). The biceps brachii in the right arm is active in both the down and up-bow movement, although it is more forceful during the up-bow (flexion of the elbow and shoulder) as it works against gravity during that motion (Shan, Visentin & Schultz, 2004). EMG analysis shows the biceps works more in the elbow movement than shoulder movement (Szende & Nemessuri, 1971). As the force of gravity is constant on the body, the deltoid and biceps brachii in the right arm have to work eccentrically against this force to control movement during the down-bow (Szende & Nemessuri, 1971). In the left forearm, the wrist and finger flexor and extensor muscles are used to control the fingering movements in the hand, whereas the flexors and

extensors in the right forearm are used to control the bow (Bejjani, Kay, & Benham, 1996; Fry, 1986; Lockwood, 1989).

Muscles do not operate independently of one another (Rosen, 1993); rather they work together to produce the desired movement by coming on and off to help. The agonist is the muscle which is contracting and it is resisted or counteracted by the antagonist muscle. These muscle functions occur in a sequential pattern during movement. For example the flexors and extensors coordinate during a movement as do the abductor and adductor muscles (Szende & Nemessuri, 1971). When executing the motions to play the violin, most of the muscles being used act in a periodic pattern. Bejjani, Ferrara and Pavlidis (1989) used EMG to look at violinists playing vibrato and found that the muscles being observed: left biceps brachii, flexor digitorum, extensor digitorum, and pronator teres, come on and off in a periodic fashion, while the deltoid is constantly active. No studies have looked at the pattern of activity of the muscles in the right arm, while playing the violin.

Quantitative Techniques

The understanding of movement patterns and muscle activity involved in playing the violin has mainly come from the use of EMG and 2D or 3D motion analysis. Electromyography and motion analysis have played an integral role in a) studying various populations, including athletes and children, b) understanding and improving movement patterns, and c) helping with injury prevention and rehabilitation. Although these techniques have proven to be useful in those areas they have been used in only a limited number of studies on musicians (Bejjani, Ferrara & Pavlidis, 1989; Lederman, 2003;

Fjellman-Wiklund, et al., 2004; Philipson, Sorbye, Larson & Kaladjeu, 1990; Berque & Gray, 2002; Levy et al., 1992; Tulchinsky & Riolo, 1994; Turner-Stokes & Reid, 1999; Shan & Visentin, 2003; Shan, Visentin & Schultz, 2004 ; Visentin & Shan, 2003).

Electromyography: EMG records the electrical activity in many motor units of a muscle. A motor unit is made up of a motor neuron and the muscle fibers that it serves. A muscle fiber is innervated by one motor neuron and one motor neuron may innervate a few or many fibers depending on the size and function of the muscle. For example, large forces are not required of the muscles which move the eye, therefore there are less motor units and subsequently less fibers being innervated by a motor neuron in that motor unit. In comparison, the biceps brachii is used to generate large forces, therefore it has more motor neurons and more fibers being innervated by each motor neuron. The motor neuron transmits an impulse, electrochemical in nature, from the spinal cord to the skeletal muscle. The impulse travels through the axon of the motor neuron to the motor endplate. The impulse facilitates the release of a neurotransmitter, acetylcholine (ACh), at the neuromuscular junction or motor endplate. The ACh combines with a receptor on the postsynaptic membrane of the muscle fiber (the sarcolemma). This site is where ions are able to move between the intra and extra-cellular fluid. The result is a change in the electrical properties, and therefore a change in potential. An action potential (AP) then spreads waves of depolarization along the muscle fiber, which travel in both directions on the sarcolemma from the motor point (Winter, D. A., 1990; Lahado, Ross & Issel, 1974; Kamen & Caldwell, 1996; De Luca, 1997; De Luca, 2002; Germann & Stanfield, 2002).

An AP is a sequence of electrical changes along the sarcolemma. The AP is what is recorded by the EMG electrodes. When a stimulus occurs the resting membrane potential, which is approximately -70mV inside the cell, is altered causing the change in polarity which results in an AP. Depolarization begins (where the cell becomes slightly less negative) as the sodium (Na^+) channels of the cell open, allowing positively charged Na^+ ions to enter the cell. The depolarization must reach a threshold, where the inside of the cell is -60 to -55mV, for the AP to continue. This threshold in the muscle fiber is reached by continued stimulation in the form of excitatory and inhibitory postsynaptic potentials. Ions can then enter the cell resulting in the change in the membrane potential. This continues until the cell becomes depolarized enough to cross the threshold resulting in an AP. The AP shows the contraction of the muscle is occurring. It is followed by a repolarization of the cell. The repolarization begins when the cell reaches +30mV where the Na^+ channels close and potassium (K^+) channels open in the sarcolemma, allowing K^+ to leave the muscle cell. This restores the cell to its polarized state. (Winter, D. A., 1990; Lahado, Ross & Issel, 1974; Kamen & Caldwell, 1996; De Luca, 1997; De Luca, 2002; Germann & Stanfield, 2002).

A raw EMG signal consists of the action potentials that occur along the membrane of a muscle cell, which in turn cause a contraction. Each AP lasts 1-2 milliseconds, and then another can be generated once the cell is repolarized, resulting in another signal being sent along the muscle cell. This depolarization and repolarization process produces the positive and negative pattern seen in the raw EMG signal. The output seen in the electromyogram consists of many single fiber action potentials grouped together to make the signal. When the action potential occurs in a muscle fiber, the same

thing is occurring in a nearby muscle fiber in the same or adjacent motor unit. Therefore what is seen in the output is a combination of the action potentials from the motor units firing in the same proximity (Figure 2). Figure 2 shows two motor units each consisting of a motoneuron and the innervated fibers within that muscle. As seen, motor unit A is innervating muscle fibers 1, 4 and 5, and motor unit B is innervating fibers 2 and 3. Action potentials occur in each muscle fiber. The action potentials produced in the individual fibers are then summed together to produce the motor unit action potential (MUAP). The MUAPs are then combined to produce what is seen in the output of the EMG. The amplitude and frequency of the action potential detected depend on the depth of the muscle fiber below the skin and therefore the distance from the electrode recording the signal to the fiber and the amount of tissue between the fiber and the electrodes. (Winter, 1990; Lahado, Ross & Issel, 1974; Kamen & Caldwell, 1996; De Luca, 1997; De Luca, 2002; Germann & Stanfield, 2002).

The use of EMG when evaluating movement can help to determine the most active muscle groups during specific activities, and to discover which muscles have the greater risk of pain or fatigue (Lederman, 2003). In musicians, the use of EMG as a method of discovery has been minimal and the research done has had a wide variety of purposes. Bejjani, Ferrara and Pavlidis (1989) attempted to identify objective and reproducible parameters of musculoskeletal functioning during the performance of vibrato using EMG, and found that there is a periodic pattern occurring in the activity of the biceps brachii, flexor digitorum, extensor digitorum, and pronator teres of the left

arm. To the best of our knowledge, there are no studies that have observed the muscle activity coordination patterns during a similar playing task without vibrato.

Fjellman-Wiklund, et al. (2004) used EMG to examine variability in string players' technique and to discover if there was intra-individual reproducibility in right and left upper trapezius muscle activity when playing, using two sessions separated by eight weeks. The study found that the right and left trapezius muscle activity was different. The left trapezius showed a constant load and the right trapezius activity was varied with respect to the period and amplitude of the EMG signal measured. There was no significant variability within each player individually on the two testing days, whereas significant variability between the different players was found. This study showed that different playing techniques can be identified using EMG data. Philipson, Sorbye, Larson and Kaladjeu (1990) wanted to compare muscle load levels, using average rectified EMG, in the biceps and triceps brachii, deltoid and trapezius, when playing the violin in various positions: standing relaxed without the violin, playing a piece at a fixed pace while sitting in a chair with good support, without good support, and standing. No differences in the load levels on the muscles assessed were found when playing in the different postures.

Research has also been done on injured musicians using the EMG technique for data collection. Philipson, Sorbye, Larson and Kaladjeu (1990) measured muscular activity in musicians with neck and shoulder pain and those without. To allow comparison between subjects, the data were normalized using isometric maximal voluntary contractions (MVC) of each muscle assessed. Musicians experiencing pain showed significantly higher levels of muscle activity in the left and right trapezius, in the

right deltoid and in the right biceps brachii, compared to participants without pain when completing the task of playing a piece.

Berque and Gray (2002) investigated muscle activity in the upper trapezius muscles in violinists and violists with and without pain in their shoulders and neck, while at rest, playing an easy piece, and playing a difficult piece. In contrast to Philipson et. al, (1990), they found that musicians who were pain-free had more upper trapezius activity during playing than the ones experiencing pain, and they also determined that variability between subjects was large. During the rest condition, the musicians with pain had a higher level of upper trapezius activity. When observing only the uninjured violinists and violist, there was more activity while playing as compared to when resting, and activity was higher when playing a more difficult piece of music. The final observation came from separating the right and left trapezius activity. Although differences were not significant, the musicians had more activity in the right trapezius when playing a more difficult piece of music, while at rest the left side was slightly more active.

Levy et al. (1992) assessed whether using a shoulder rest would relieve some of the tension in the upper trapezius and sternocleidomastoid muscles in a group of violinists, some of whom had experienced pain in the past but had no problems at the time of testing. Muscle activity data were collected from right sternocleidomastoid, left trapezius, anterior deltoid, and biceps brachii while playing with and without a shoulder rest. Using a shoulder rest was shown to decrease activity in the trapezius and sternocleidomastoid.

Electrode placement: Pairs of surface electrodes are placed over the belly of the muscles, perpendicular to the muscle fibres, to acquire the electrical signal when the

muscle is activated. In playing-related studies, the electrodes were placed on many parts of the upper body, including the upper back and shoulder region, the left deltoid (Bejjani, Ferrara, & Pavlidis, 1989; Levy et al., 1992; Philipson et al., 1990; Shan, Visentin & Schultz, 2004), the right deltoid (Philipson et al., 1990; Shan, Visentin & Schultz, 2004), the right (Berque & Gray, 2002; Fjellman-Wiklund et al., 2004; Philipson et al., 1990) and the left (Berque & Gray, 2002; Fjellman-Wiklund et al., 2004; Levy et al., 1992; Philipson et al., 1990; Shan, Visentin & Schultz, 2004) upper trapezius, as well as the middle trapezius (Shan, Visentin & Schultz, 2004) and the sternocleidomastoid (Levy et al., 1992). The activity from the muscles in the arm has been studied with electrodes on the left (Bejjani, Farrara, & Pavlidis, 1989; Levy et al., 1992; Philipson et al., 1990) and right (Philipson et al., 1990; Shan, Visentin & Schultz, 2004) biceps brachii, as well as both the left (Philipson et al., 1990) and right (Philipson et al., 1990; Shan, Visentin & Schultz, 2004) triceps brachii, the left flexor digitorum and extensor digitorum, the left pronator teres (Bejjani, Farrara, & Pavlidis, 1989) and the right extensor carpi radialis longus (Shan, Visentin & Schultz, 2004). One study placed electrodes on many small forearm muscles (Shan & Visentin, 2003).

Motion Analysis: By putting reflective markers on anatomical bony landmarks, movement is captured by infrared or video cameras and coordinates are assigned to each marker position over time. Through this a model can be created which allows calculation of kinematic variables such as joint angles, limb and joint displacement, velocity, and acceleration. Motion analysis can be done in 2D or 3D and provides a detailed description of movement patterns. This technique has been used to help athletes improve their performance and to prevent injuries (Kelly, Backus, Warren, & Williams, 2002). It

has also been used for gait analysis, workplace task analysis, and computer animation, however very few studies have looked at musicians.

Tulchinsky & Riolo (1994) used 2D analysis to characterize the movement of the bowing arm by examining the range of motion (ROM) of the right elbow joint. Turner-Stokes and Reid (1999), Shan and Visentin (2003), and Visentin and Shan (2003), used 3D motion analysis to study the playing movement. Shan and Visentin (2003) analyzed the motions of both the right and left arms, looking at the ROM not only at the elbows but also at the shoulders and wrists. They also assessed elbow height, bow speed, and effect of changing the string level (E to G) on elbow, shoulder and wrist ROM. Visentin and Shan (2003), recorded sound and used motion capture to determine kinematics of the bow and bowing arm, to assess load levels (using moments to find forces) in terms of quantity, influenced by the string played and tempo, and quality in terms of the type of load. Turner-Stokes and Reid (1999) developed and tested a simple clinical protocol to analyse 3D bowing movement in string players. They looked at where the differences lay in players' technique, and compared ROM at the shoulder, elbow and wrist joints between violinists, violists, and cellists. It was this protocol that provided the basis for the motion analysis data collection methods used in our study.

Marker placement: Markers have been placed on the right ulnar styloid, lateral epicondyle of the humerus, and acromion process in order to find the range of motion of the right elbow required to bow the violin (Tulchinsky & Riolo, 1994). Turner-Stokes and Reid (1998) added markers, in addition to the markers mentioned above, on the head of the clavicle, 5th meta-carpophalangeal joint, spinous processes of the 7th cervical vertebra (C7) and 2nd thoracic vertebra (T2), and the olecranon process of the elbow.

These marker locations were shown to give reproducible results when calculating ROM, at the shoulder and elbow, between trials requiring the takedown and set up of equipment and replacement of markers. Other protocols have used 24 markers on the upper body and three more on the bow (Shan & Visentin, 2003) and 30 markers on the body and bow (Visentin & Shan, 2003), to give a different perspective on the violinist's motion.

Combination of techniques: It has been suggested that when analyzing the multiple planar movements which occur while playing, EMG should be collected simultaneously with 3D motion data in order to better understand the playing movement (Tulchinsky & Riolo, 1994). Biomechanical modeling has been recommended as a means to integrate this information and to connect various techniques for studying movement patterns (Visentin & Shan, 2004). To date, one study has combined both EMG and motion analysis to analyse the motion and muscle activity of professional musicians playing the G-major scale at various bowing speeds (Shan, Visentin & Schultz, 2004). The synchronized data were used to correlate joint moments and muscle activity to see if there was a relationship.

Technology is now available to quantitatively assess the demands placed on a violinist when playing. The usefulness of the multidisciplinary approach has been shown. By combining both EMG and motion analysis a better understanding and overall view of the violinists' movements can be determined. This will result in an improved method to assess and prevent injuries, by quantitatively characterizing the patterns while playing (the joint ROM and muscle activity).

CHAPTER 3: METHODS

Muscle activity, assessed with EMG, and joint ROM and angular velocities, calculated from motion analysis, were determined while the violinists played five bowing cycles on each of the four strings (G-D-A-E) at a controlled tempo. Subjects were split into two groups, based on their experience, for analysis.

Participants

Participants in our study were musicians who had played the violin for at least two years and who were injury-free at the time of testing. Participants were assigned to an expert or novice group depending on how many years they had played. We determined this from a questionnaire asking about playing experience (Appendix A). The expert group consisted of musicians who had played the violin and taken lessons for seven or more years, and who were part of an orchestra group. Novices were the rest of the participants not meeting those criteria. Twelve violinists participated in the study, six in the novice group ($age = 26 \pm 10.71$ yrs; $ht = 165.42 \pm 10.7$ cm; $mass = 61.48 \pm 18.37$ kg) and six in the expert group ($age = 32 \pm 15.4$ year; $ht = 166.4 \pm 10.7$ cm; $mass = 62.6 \pm 8.65$ kg). After a complete explanation of the study using the information sheet (Appendix B), subjects gave their informed consent by signing a consent form (Appendix C). Parents or guardians gave written informed consent for subjects who were minors. Ethics clearance for the study was given by the Brock University Research Ethics Board (04-005).

Sampling Techniques

Each participant's skinfold measurements were taken from suprailiac, subscapular, triceps, and biceps sites, and summed.

Two techniques quantified the muscle activity and motion patterns: EMG and 3D motion analysis respectively. The EMG data were collected using a Noraxon telemetered system (Noraxon USA Inc., Scottsdale, AZ). Seven channels of EMG recorded the muscle activity involved in the movements analysed. Three-dimensional motion data were collected using Peak Motus (Peak Performance Technologies, Englewood, CO) with eight infrared cameras set up around the room picking up the six reflective markers on the subject.

Instruments

To capture the motion we placed reflective markers on the following bony landmarks: right and left acromion processes, C7 vertebra, right lateral epicondyle of the humerus, right ulnar styloid, and right 5th metacarpophalangeal joint.

Pairs of silver-silver chloride surface electrodes (AmbuBlue Sensor, Demark) were used to record muscle activity. Before the electrodes were placed on the participant, we prepared the skin by shaving the area, applying Lemon Prep (Mavidon Medical Products, USA), and cleaning the site with rubbing alcohol. Muscle activity was recorded from seven muscle groups on the upper body: the right and left upper trapezius, the right anterior deltoid, biceps brachii, and triceps brachii, and the left wrist and finger flexors and extensors. Only the data from biceps, triceps and deltoid were analysed for this study. We placed the electrodes over the belly of the muscles studied and secured wires to the upper extremities by wrapping with a tensor bandage.

Procedures

Before data were collected, a calibration for the Peak Motus system was completed, and maximal voluntary contractions (MVC) of each of the muscle groups being assessed were obtained. This was done so that participants' EMG data could be presented as a percent of their MVC, therefore allowing data to be compared between violinists. We obtained the three-second MVCs while the participant sat in a chair, in the same position he/she completed the playing task. Clinical manual muscle testing procedures were used to elicit maximal activity from each muscle group (Daniels & Worthingham, 1972). For example, upper trapezius produces shoulder girdle elevation, therefore the violinist attempted to elevate his shoulders (shrugging) while a maximal force was applied downward by the researcher, attempting to depress the shoulders. Other resisted movements used were: deltoid – shoulder abduction, biceps – elbow flexion, triceps – elbow extension, wrist extensors – wrist extension, wrist flexors – wrist flexion.

Once the MVC for each muscle was obtained, participants were given time to play their violin to get used to the recording equipment. The experimental playing task consisted of five bowing cycles (one bowing cycle equals one down-bow followed by one up-bow) on each string (Figure 3) with the third finger in first position. The tempo was four beats per bow at a pulse of 100 beats per minute, with no vibrato. This pattern was repeated on each of the strings starting on G and continuing onto D, then A, and ending on E. The down-bow motion consists of shoulder extension (decrease in angle), elbow extension (increase in angle), and one of shoulder abduction or adduction depending on the player's technique. The up-bow motion is the opposite and requires

shoulder flexion (increase in angle), elbow flexion (decrease in angle), and either shoulder abduction or adduction (Figure 4). Subjects were given no specific instructions on how their playing should sound.

Once the data were collected, we identified the marker paths and the bowing cycles were divided by strings for further analysis. The marker coordinate data were filtered using a 2nd order Butterworth low pass filter with a cut off frequency of 10 Hz (Winter, 1990). The EMG data were band pass filtered at 10-500 Hz and then further analyzed in Matlab (The MathWorks, Inc., Natick, MA)

An upper extremity model was created in Peak Motus to allow calculation of the shoulder and elbow angles. The shoulder angles measured were anatomical 180 degree angles with respect to a plane of reference. The flexion and extension angle at the shoulder was calculated using the right acromion process as the vertex, the right lateral epicondyle as the second point, and was projected onto the sagittal plane. The abduction and adduction angle at the shoulder was calculated using the same points, and was projected onto the frontal plane. The elbow angle was a vector angle measuring flexion and extension between the upper arm and forearm, using the right acromion and right ulnar styloid markers as points and the right lateral epicondyle as the vertex (Figure 5). These values were calculated based on a local coordinate system with the origin at the C7 vertebra. We determined the maximum and minimum angles, ranges of motion (ROM), and angular velocity at each joint, on each string.

To examine the muscle activity required to perform the movements, the data were analysed using a custom software program written in MatLab. The EMG data were expressed as a percent of the participants' MVC, creating normalized EMG, and were

plotted against the synchronized motion data (Figure 6). Muscle activity values were obtained from the middle 20% of the range of joint motion (Rothstein, Delitto, Sinacore & Rose, 1983). The root mean square (RMS) for the muscle activity in that 20% section of the movement was then calculated. An RMS value was calculated for each up-bow and down-bow motion separately. The mean of the RMS values for the five up-bow and down-bow motions was then determined. This was done on each string for each movement (shoulder flexion/extension or abduction/adduction and elbow flexion/extension). For example, the biceps brachii RMS values for the five up-bow motions (during elbow movement) on the G string were averaged, for each participant. This calculation was repeated for the five down-bows on the G string. Data for each string were treated in the same fashion to represent the muscle activity for the biceps brachii. These steps were completed for each joint movement being analysed to find the activity of the muscles involved in that movement. These included the biceps and triceps brachii during shoulder and elbow flexion/extension, and the deltoid during shoulder abduction. Each individual's mean percent MVC was identified for each of the four strings for each movement. Using the MVC allowed for comparison between participants. This process was also completed to find the participants' angular velocity during the middle 20% of each movement.

Statistical analysis in STATISTICA (StatSoft, Inc, Tulsa OK), included a general linear model repeated measures analysis to look for differences in the violinists' maximum and minimum joint angles, ROM, angular velocity, and muscle activity on each string, depending on their playing experience. The analysis was a 2 x 4 design where the two independent variables being analyzed were experience and string. The

“between” variable was the experience level, experts and novices. The “within” variable was the four strings, G, D, A, and E. This analysis identified any main or interaction effects and statistically significant differences. The Tukey HSD post hoc test was used to pinpoint the differences. Significance was set at $p \leq 0.05$.

CHAPTER 4: RESULTS

Subject characteristics are presented in Table 1. There were six subjects in each group: novice and expert. The bowing task had the violinist start with the bow in the up-bow position and then consisted of the down-bow movement followed by the up-bow movement. Each movement, elbow flexion and extension, shoulder flexion and extension, and shoulder abduction, was analyzed across the four strings: G, D, A, E. The range of motion (ROM), maximum and minimum joint angles, angular velocity, and muscle activity levels were determined. An example of one participant's data across the four strings is presented in Figure 7.

Down-Bow Motion

The down-bow movement required elbow extension and shoulder extension with the shoulder held in varying degrees of abduction, depending on the string being played. Elbow angle increases with extension and reaches a maximum in the down-bow position. Shoulder extension angle decreases in the down-bow movement reaching a minimum value at the bottom of the movement. Biceps brachii, triceps brachii, and deltoid are the muscles most involved in these movements.

Elbow Extension: Mean elbow ROM increased slightly across the strings for the novice players and was virtually unchanged for the expert group (Figure 8). This pattern was mirrored by the mean maximum angle values which changed very little for the experts (G: 133°, D: 129°, A: 127°; E: 127°), and increased slightly for the novices (G: 125°, D: 127°, A: 128°, E: 131°).

The novice group's mean angular velocity increased from string to string. The experts' angular velocity was unchanged except for a small decrease on the A string (Figure 9).

During elbow extension mean biceps activity for the novice players was nearly double that of the expert players (Figure 10 and Appendix F). There was no consistent pattern in the muscle activity for either group across the strings (Figure 10). Novice players had a higher level of triceps activity than the experts. Novice players' triceps activity decreased across the strings, whereas the experts triceps activity was constant (Figure 11 and Appendix F). The novice players' triceps activity was lower than the biceps, whereas the expert players had slightly lower biceps activity than triceps activity across the strings.

Shoulder Extension: Shoulder flexion and extension ROM increased for both groups as they moved across the strings. The expert group had a larger ROM than the novice groups for all strings (Figure 12 and Appendix F). The minimum shoulder extension angle decreased for both expert (G: 80°, D: 68°, A: 60°, E: 53°) and novice (G: 86°, D: 70°, A: 60°, E: 48°) groups across the strings (Appendix F).

Angular velocity during shoulder extension for both groups showed a similar increase across the strings (Figure 13 and Appendix F).

During shoulder extension, the novice group activated both biceps and triceps to higher levels across the strings than the expert group (Figure 14 and Appendix F). The novice biceps activity decreased across the strings, whereas the expert biceps activity was virtually unchanged with a slightly higher level of activity on the E string (Figure 14). The same pattern in triceps activity is seen for both the expert and novice players across

the strings (Figure 15). Figures 14 and 15 show that the experts' triceps and biceps activity across the strings was similar, and the novices had greater biceps activity than triceps activity.

Up-Bow Motion

Elbow flexion and shoulder flexion are required during the up-bow motion. As with the down-bow motion abduction angle at the shoulder changes depending on the string being played. The minimum angle value at the elbow indicates the degree of flexion at the end of the up-bow movement. The maximum angle indicates the position of most shoulder flexion at the end of the up-bow movement. The biceps brachii, triceps brachii, and deltoid muscles are also involved in the up-bow movement.

Elbow Flexion: The minimum elbow flexion angle ranged from 68 to 70° for the experts and 63-65° for the novices across the strings.

The expert violinists' angular velocity values decreased slightly across the G, D and A strings, and then increased on the E-string during elbow flexion, whereas the novice players' values showed no clear pattern, but were relatively similar, across the strings (Figure 16).

The expert and novice groups' biceps activity during elbow flexion increased across the strings with a slight decrease on E (Figure 17). The triceps activity across the strings decreased for both experience groups (Figure 18). Both the biceps and triceps activity were higher during elbow flexion for the novice group than the expert group (Figure 17 and Appendix F).

Shoulder Flexion: The maximum angle calculated across the strings for shoulder flexion decreased for both the experts (G: 110°, D: 103°, A: 98°, E: 95°) and novices (G: 102°, D: 92°, A: 87°, E: 77°) (Appendix F).

During shoulder flexion the angular velocity increased for both experience groups across the strings. The expert violinists showed a slightly higher angular velocity value on each string compared to the novices (Figure 19 and Appendix F).

The biceps activity was higher for the novice players across the strings as compared to the expert players, as was the triceps activity (Figure 20, 21 and Appendix F). The expert group's biceps activity increased across the strings with a slight decrease on E and for the novice group the biceps activity increased with a slight decrease on D (Figure 20). There was no clear pattern in the triceps activity for the novice and expert violinists during shoulder flexion (Figure 21).

Shoulder Abduction

The shoulder abduction ROM decreased across the strings for both experience groups and the expert players had a greater ROM than the novice players on all four strings (Figure 22). The maximum angle during shoulder abduction decreased for both the experts (G: 176°, D: 131°, A: 104°, E: 78°) and the novices (G: 119°, D: 103°, A: 76°, E: 57°) (Appendix F).

Both groups' angular velocity during shoulder abduction decreased, except for a slight increase on the D-string in the novices and the E-string in the experts (Figure 23).

The deltoid activity during shoulder abduction was higher for the novice violinists across the strings (Figure 24 and Appendix F). The experts' deltoid activity during

shoulder abduction decreased across the strings (Figure 24 and Appendix F). The deltoid activity for the novice players also decreased (only a small amount between G and A) with a slight increase on the D string (Figure 24).

Muscle Activity Patterns

The triceps and biceps muscle activity, during both the down and up-bow shoulder and elbow motions, exhibited a periodic 'on/off' pattern, while the deltoid was seen to come on and stay on throughout the entire movement (Figure 7). The bursting pattern of the biceps and triceps is somewhat obscured by a large baseline of activity. This is due to the low %MVC being used for the movements; therefore the bursting pattern is not as evident. In spite of this, it is still clear that the experts' muscle activity displayed the periodic pattern more consistently than the novices' did (Figure 25).

CHAPTER 5: DISCUSSION

Multidisciplinary analysis, combining EMG and motion analysis, was used to determine the patterns of movement and muscle activity occurring in the bowing arm in expert and novice violinists. A thorough knowledge of the movement patterns and muscle activity required to perform the bowing movement is needed to begin to understand the causes of overuse injuries that plague musicians.

Range of Motion across the Strings

Elbow ROM was not significantly different across strings, increasing slightly in the novice group (Figure 8). These results agree with previous results in the literature (Tulchinsky & Riolo, 1994; Shan & Visentin, 2003). Similar elbow ROM values across strings suggest that the different playing positions required to produce sound on each string (Figure 3) are created at the shoulder joint, rather than at the elbow. Our subject groups were not different in height (Table 1), and as a result, arm length, and they all played full size violins and had bows of similar length, therefore no differences in elbow ROM were expected.

Shoulder flexion and extension ROM increased across the strings for both experts and novices, especially on the two upper strings, A and E (Figure 12). The shoulder flexion and extension ROM values were within the ranges found from other research as was the increase in the ROM across the strings (Turner-Stokes & Reid, 1999; Shan & Visentin, 2003). This supports the idea that it is shoulder movement differences, particularly flexion and extension, which create the different movement pattern seen on each string.

Shoulder abduction maximum angle and ROM decreased across the strings for both groups, with the experts having higher values than the novices. This finding is unlike what others found, which was a similar abduction ROM across the strings, with it only being slightly less on the E string (Shan & Visentin, 2003). This could be due to the methods used to determine the shoulder abduction angle, as they found the angles with respect to the bodies' anatomical system, and we determined them based on a local coordinate system. The right arm needs to be held at different heights to play on the various strings, therefore it was expected that the abduction angle would change as the bow moved across the strings.

The angle of the bow changes when playing across the four strings, as seen in Figure 5. The shoulder is at the greatest abduction angle when playing on the G string. Then as the bow moves across the strings, from D to A to E, the shoulder abduction angle decreases. Since the elbow ROM in the right arm does not change when going across the strings, it appears that the shoulder angles determine the changes in bow position from string to string.

The right arm has been shown to have larger movement patterns, at the shoulder, which are influenced by the string the violinist is playing on (Shan & Visentin, 2003). Shan and Visentin (2003) hypothesized that the control of the bowing movement transfers from the shoulder joint on the E-string to the elbow joint on the G-string, because the shoulder flexion and extension ROM is greatest on the E string, whereas the elbow ROM is greatest on the G-string. This was suggested as the ROM increased from G to E for the shoulder and decreased for the elbow in their subjects, therefore when the ROM is the largest at that joint it is the one controlling the movement (Shan & Visentin,

2003). Our findings were slightly different. The elbow ROM was unchanged across strings suggesting that the bowing action is influenced mainly by the shoulder movement, due to the large change in ROM across strings during shoulder flexion and extension. Using Shan and Visentin's (2003) reasoning; since the shoulder flexion and extension ROM increased across strings, whereas the elbow ROM remains unchanged, the control for the movement would be more influenced by the shoulder than the elbow.

The Influence of Gravity across the Strings

Since gravity always acts downward on the body, anything moving in an upward motion is acting against it. When the bow is on the G string the shoulder is in the most abducted and most flexed position. As progression across the strings occurred, shoulder flexion and abduction maximum angles decreased, as did shoulder abduction ROM, whereas shoulder flexion and extension ROM increased. This change in arm orientation changes the demands on the muscles moving the shoulder and elbow joints. The muscles have to work harder when contracting to move the joints if the movement is occurring against gravity. For example, while deltoid is constantly active to maintain shoulder abduction, more muscle activity is needed to play on the G string than on the E string, where the degree of abduction is less. Conversely, biceps activity was expected to increase, moving across strings, because the gradually more dependent position of the arm meant more of the flexion and extension movement was performed against gravity. During the opposite motions, on the down-bow, even though the movements are with gravity, the deltoid and biceps brachii still have to act eccentrically to keep the arm from dropping.

Deltoid

The maximum shoulder flexion angle occurred when the violinists played on the G string, as did the maximum abduction angle and greatest shoulder abduction ROM. Playing on the G string produced the highest value of deltoid muscle activity which then decreased across the strings, as did the shoulder abduction and flexion maximum angles and the abduction ROM (Tables 15 and 18). A significant difference between the G and E string was found for the deltoid activity during shoulder abduction in the expert group. Shan, Visentin and Schultz (2004) found that the right deltoid activity was highest on G and lowest on E regardless of the varying tempos they tested. By combining EMG with internal loads and muscle lengths, they concluded that the deltoid muscle has to bear the greatest load in violinists (Shan, Visentin & Schultz, 2004).

Shoulder load is influenced by the string that the violinist is playing on. This is due to the effect gravity has on the arm and the effort that must be exerted to hold the arm at the appropriate levels (Visentin & Shan, 2003). A high correlation was found between the right deltoid activity and shoulder load when the tempo was either slow or medium (Shan, Visentin & Schultz, 2004) indicating that the deltoid is the main contributor to shoulder movements (as opposed to the other muscles assessed in the study: upper and middle trapezius, triceps, and biceps). At slow speed (25 bows per minute) the deltoid was the most loaded muscle. In our study it was observed that the deltoid had the highest muscle activity across the strings, when compared to the biceps and triceps when subjects played at 25 bows per minute. At the higher tempos the deltoid plays a smaller role and multiple muscles shared in the control of the bowing movement (Shan, Visentin &

Schultz, 2004). We did not test at higher speeds and therefore cannot comment on this observation. At slower speeds it has been suggested that the deltoid participated in managing the bow control (or direction of the stroke, which is based on the bow movement corresponding with the peak to trough movement of the enveloped EMG) and string level adjustments, whereas during the faster tempos it controlled only the string levels (Shan, Visentin & Schultz, 2004).

The deltoid activity in the present study had a consistent pattern, being 'on' throughout the movement, and did not show a periodic pattern as the triceps and biceps activity did (Figure 7). No other studies have examined the periodic, or 'on/off', muscle activity in the bowing arm. Bejjani, Ferrara, and Pavlidis (1989) showed that in the left arm, biceps brachii, flexor digitorum, extensor digitorum, and pronator teres followed a periodic pattern and deltoid was on constantly during a vibrato playing task. The deltoid acts as a support muscle in the shoulder and is therefore always 'on', to support the violin on the left side and to maintain arm and bow position on the right.

Biceps Brachii

While the deltoid is a dominant factor controlling shoulder position, the biceps brachii appears to be the muscle controlling the elbow. In the present study, biceps activity was greater during elbow flexion and shoulder flexion than during elbow extension and shoulder extension. Shan, Visentin and Schultz (2004) found similar patterns of activity and concluded that the biceps brachii is responsible for changes in the elbow movement from extension to flexion and that it works against the effect of gravity especially on the up-bow motion (during elbow flexion). This was shown by a spike

increase in biceps EMG when changing to up-bow against gravity at slower speeds. Shan, Visentin and Schultz (2004) showed through correlation of the right biceps EMG and the elbow flexion/extension movement, that biceps activity initiates the direction the bow was moving (down or up) at all playing tempos, and that biceps was more active in direction changes, from down bow to up bow than in controlling the whole bowing movement.

Biceps activity, measured as percent MVC, was virtually the same across the strings for each group (Figure 10, 14, 17, and 20). Similar results are found in the literature (Shan, Visentin & Schultz, 2004). This could be because the elbow flexion and extension movement ROM is not changing across the strings. However, it must be taken into account that the shoulder flexion and extension ROM data does not support this, as it changes across the strings.

Triceps Brachii and Biceps Brachii

The triceps brachii was the least active of the three muscles observed in this study. Between the strings, triceps activity changes were not observed. Biceps and triceps activity in the bowing movement can be described in terms of agonist and antagonist actions. The agonist muscle produces a movement; the antagonist muscle acts to slow or stop the movement because it produces the opposite action. This holds true for the triceps activity corresponding with the biceps activity for the violinists seen in this study. Throughout all the movements for bowing there was never a time when any muscle activity was at a baseline. This shows that all muscles always work in some capacity to facilitate or help in the movement process. For example during elbow flexion movement

the biceps is the agonist and is more active than the triceps which is the antagonist during this movement; whereas during elbow extension the opposite should be occurring.

In the present study, the biceps activity is higher than the triceps activity for both groups during elbow flexion (Figure 17 and 18). During elbow extension the triceps activity is higher than the biceps in the expert group, but not the novice group (Figure 10 and 11). The same relationship is seen in the shoulder flexion and extension movement (Figure 20, 21, 14, and 15). The 'on and off' pattern as described during movement of agonist and antagonist muscles can be seen in the expert's movement, as shown in Figure 25. As the movement goes from the up-bow to the down-bow position during extension, the triceps is 'on' and during the movement triceps activity decreases as biceps activity increases. The biceps has the highest burst of activity during the down to up-bow transition (flexion). The activity of these two muscles, triceps and biceps, is periodic ('on' and 'off') during the flexion and extension motions at the shoulder and elbow. The activity for both muscles is never completely 'off', although it is usually less while the muscle is acting as the antagonist, unless it is working eccentrically to control the motion during a braking movement.

Experts versus Novices

No other studies have examined expert-novice differences in these movements. Past research grouped all levels of experience (Shan & Visentin, 2003) or looked at professional musicians separately (Philipson, Sorbye, Larson & Kaladjeu, 1990). The experience groups in our study were based on how long subjects had played the violin and if they had played in an orchestra. Our novice group had played the violin for at least

two years, with no orchestra experience, and the expert group had played for seven or more years, with orchestra involvement. The experts were shown to have played for an average of 10 years longer than the novices when comparing means. Previous literature on injuries in musicians, using questionnaires, suggests that injuries are primarily based on repetition of the skill (Zaza & Farewell, 1997), although no research has been done to check to see if novices do the movements differently from more experienced players, possibly presenting an alternate view as to causes of playing related injuries. The present study looked at each group separately to determine any differences between the various factors: movement patterns and muscle activity.

The elbow ROM was similar between the groups although the novice group showed a consistently larger ROM for all the string levels (Figure 8). Shoulder ROM for all motions, flexion and extension and abduction, was greater in the expert group for all strings (Figure 12 and Figure 22). These findings are different than those reported by Turner-Stokes and Reid (1999) who demonstrated that both the school age violinists and the mature professionals tested in their protocol, produced similar joint angles. This is possibly due to the differing criteria used to distinguish the experience levels. Our study used years played and orchestra participation to distinguish the novices from the experts, whereas their study used age as the main criterion. The larger ROM seen for the experts at the shoulder joint may be due to the experts using the full bow to produce the desired sound throughout the movement, whereas the novices did not.

With respect to the muscle activity, the novice players used a greater %MVC for all muscles compared to the experts in almost every movement completed. Significant novice-expert differences were found for the biceps activity during shoulder and elbow

flexion and extension (Figure 10, 14, 17, and 20), triceps activity during elbow extension and flexion and shoulder flexion (Figure 11, 18, and 21), and deltoid activity during shoulder abduction (Figure 24). Experts demonstrated biceps activity that was greater than triceps activity during shoulder and elbow flexion (Figure 17, 18 20, and 21), whereas during shoulder and elbow extension triceps activity was greater than biceps activity (Figure 10, 11, 14, and 15). This pattern of agonist-antagonist activity was expected. The novice violinists had similar activity patterns in some instances but without the consistency of the experts, and their muscle activity was higher in all movements.

In motor learning it has been suggested that long term training leads to highly stable control patterns in individual athletes and performances of a professional calibre. Shan and Visentin (2003) showed that the elbow ROM data obtained were consistent between trials. This finding lead them to believe that comparisons between professional and less advanced violinists could help to improve methods of teaching and find key factors that influence the repeatability of the skill. In our study, the expert groups' joint ROM and muscle activity followed a more consistent pattern than the novices. This finding is possibly due to the fact that the repetition that comes with experience has taught the violinists what is needed to play.

With respect to muscle activity it has been suggested that once a motor task becomes well learned, a change from coactive patterns to reciprocal patterns occurs (Basmajian, 1977). This is evident in our study as the expert group followed a more predictable reciprocal pattern of muscle activity than the novices, whose muscle activity was seen to be more coactive (Figure 25). Shan, Visentin and Schultz (2004) stated that less experienced violinists have a less pronounced, or even absent, relaxation phase

directly after a bow direction change. We did not assess this specifically in our data, however more muscle activity was occurring during every movement and across all strings for the novice players as compared to the experts (Figure 10, 11, 14, 15, 17, 18, 20, and 21), therefore the muscles were less active for the experts than novices. It was expected that the biceps and triceps muscle would act in a more periodic 'on/off' pattern, but the novices didn't demonstrate this in the manner that the experts did (Figure 25). This suggests that experts and novices create the bowing movement differently. A possible explanation for this is that the experts require less activity to produce the movement, and did not exert as much of their muscle capacity because they knew what amount of activity was needed to complete the appropriate movement. Due to lack of familiarity with the movement, the novice group contracted all their muscles thinking this was required, instead of allowing them to come on and off. It could be hypothesized that the less experience a violinist has, the more muscle activity they will be exerting when playing throughout the movement. As they become more skilled, the on and off pattern will be more apparent. It is a well established principle that there should be a minimal amount of energy required to achieve a movement, produced by activating only the necessary muscles (Basmajian, 1977). Fjellman-Wiklund, Grip, Karlsson and Sundelin (2003) suggested that in musicians this principle is demonstrated by optimal playing technique which includes efficient motion patterns and avoids unnecessary movements and muscle activity. As demonstrated in the present study, the expert group, having more years of experience, followed this principle more closely than the novices did. As the experts practice and perfect their playing technique and sound production, they then realize how to create the movement while using the least amount of muscle activity to

achieve the desired sound. As the novices improve their playing and technique they will acquire a more consistent pattern of movement and a more reciprocal pattern of muscle activity. Cumulative effects of too much muscle activity have been shown to lead to injuries. If players use the least amount of muscle activity needed to complete the skill, it would be expected that injury rates would decrease as there would be a smaller amount of muscle activity exerted to produce the desired outcome. This, however, does not take into account the effect of repeated bouts of muscle activity.

Angular Velocity

In this study, angular velocity was related to the ROM at the joint: the greater the ROM, the higher the angular velocity, which can be seen for shoulder flexion and extension (Figure 12, 13, and 19). In the elbow movement both the angular velocity and ROM are consistent across strings (Figure 8, 9, and 16). This is to be expected because the playing tempo was controlled. No previous research was located which assessed joint angular velocity during the bowing movement. Angular velocity indicates how fast the joint is moving during a specific movement. Higher velocities could contribute to injuries occurring at the joint. The composer sets the tempo at which the music is played, either precisely, or within a given range; therefore this is not always controlled by the violinists. In our subjects, the highest angular velocity values are found right before the change from up to down-bow or down to up-bow (Figure 7). As players become more skilled and are able to play at a faster tempo, thus increasing angular velocity, the potential stress on joints and possibility of injury would increase. Further research into this possible link is warranted.

Injuries

Playing related injuries in musicians include a number of disorders and injuries which fall into the category of overuse or misuse syndromes. This syndrome occurs when parts of the body are pushed to their extreme, exceeding physiological and biomechanical limits through overload or the repetition of one movement. Micro-traumas producing pain and tenderness result when muscles are pushed beyond their normal physiological or biomechanical limits (Bejjani, Kay, & Benham, 1996; Lederman, 2003; Shan & Visentin, 2003). Factors that are directly related to overuse syndrome in musicians include the genetic makeup of the violinists (which cannot be altered), the techniques used when performing, and the time combined with intensity (repetition) of playing and practicing (Heming, 2004; Knishkowsky & Lederman, 1986; Lambert, 1992; Lederman, 2003; Lockwood, 1989; Shan & Visentin, 2003; Zaza & Farewell, 1997; Fry, 1986; Knishkowsky & Lederman, 1986; Liu & Hayden, 2002).

Injuries that musicians are susceptible to do not mirror those of sport or accident situations, as these injuries are usually a result of excessive loads exceeding physiological limits that produce a percent MVC greater than 100% in a single instant (Shan, Visentin & Schultz, 2004). Rather, musicians appear to acquire overuse injuries from small tissue loads applied repetitively. In our study, triceps activity ranged from 4 to 6%MVC and biceps was active from 4 to 12%MVC. Deltoid activity ranged from 7 to 20%MVC. This range of activity has been seen in other studies and has been suggested to fall within “safe” physiological limits, however, duration (i.e. playing time) must still be considered. When accumulating these demands over time, limits may be exceeded and injuries may result (Shan, Visentin & Schultz, 2004).

The bowing action does not require an extreme range of shoulder or elbow joint movement, as shown by the minimum and maximum joint angles recorded. This suggests that ligaments are not being overly stressed to maintain joint integrity.

The neck, back, shoulders, forearms, hands, and wrists are the sites most affected by overuse syndromes in musicians (Bejjani, Kay, & Benham, 1996; Berque & Gray, 2002; Dawson, 1998; Fry, 1986; Heming, 2004; Lambert, 1992; Levy et al., 1992; Liu & Hayden, 2002; Lockwood, 1989; Zaza, 1998). The highest rates and severity of injuries have been demonstrated at the shoulder joint, specifically the left shoulder, the front of the right shoulder, and the rotator cuff (Fry, 1986; Hiner, Brandt, Katz, French, & Becxkieqicz, 1987; Lambert, 1992; Larsson et al., 1993; Lockwood, 1989; Knishkowsky & Lederman, 1986). There are no reports in the literature of injury to biceps brachii due to violin playing. Its relatively large size and the low muscle load demand of playing may account for this (Shan, Visentin & Schultz, 2004). We also observed low levels of bicep activity in the bowing task which would support this observation. There has been no specific assessment of the demands on triceps brachii, however our results would suggest that the demands on this muscle are also low, as seen in the less than 6%MVC required to perform the bowing task assessed.

The action of deltoid in the bowing movement appears to be different from biceps and triceps. EMG analysis revealed constant activity throughout the bowing movement as deltoid maintained the abducted shoulder position. A smaller shoulder flexion/extension ROM was found on the G-string (Figure 12) and this has also been suggested as a contributor to shoulder injury, as static loads have a greater potential for causing injury than dynamic loads (Visentin & Shan, 2003). This is consistent with injury data which

show that the incidence of right and left shoulder injuries is about the same with 51% reporting an injury in the right shoulder and 49% in the left (Fry, 1988; Fry, 1986; Visentin & Shan, 2003). In violinists, the left shoulder acts primarily statically (termed “quasi-static”), to maintain the violin position, and the right shoulder is only slightly more dynamic maintaining the required abduction angle for correct bow movement. Shan and Visentin (2003) stated that the dynamic characteristics of the shoulder are increased as the bow moves from the G to the E string and it has been suggested that playing on the G string is more physically tiring than playing on E. While fatigue was not a factor in our protocol, we did observe the most deltoid activity on the G string, suggesting that over time, it would be more tiring to play on the G string, where the shoulder is most abducted. In addition, when the shoulder is fully abducted on the G string, the deltoid is at a shortened length, and there is a great deal of overlap between the actin and myosin filaments. In this shortened position it is more difficult to generate force (Lieber, 1992). Our observations support the findings that the deltoid is the most injury prone and affected area for a violinist, as we showed that the deltoid exhibited the most muscle activity and was ‘on’ for the entire movement (Fry, 1988; Shan & Visentin, 2003).

CHAPTER 6: CONCLUSIONS

A multidisciplinary approach combining motion analysis and EMG was used to study the bowing motion. The results were related to previous research, including injury statistics, to show that these quantitative techniques can provide information useful for understanding the tissue stresses which may lead to injury.

Only a small amount of activity was required from biceps, triceps and deltoid to produce the bowing movement. Therefore, injuries are probably not caused by the size of the forces required, but by the repeated application of small forces. Because deltoid was activated continuously during the movement, while biceps and triceps were activated in a periodic pattern, and its level of activation was highest, deltoid may be most prone to injury of the three muscles studied. This activity pattern was the same for both groups, however novices and experts appear to produce the bowing movement differently. Generally, the novices used a larger percent of MVC in all three muscles to perform the movement compared to the experts, and the experts used a larger ROM at the shoulder than the novices. The agonist/antagonist roles played by biceps and triceps were more clearly seen in the expert group's EMG data than in the novices'.

The sample size in this study (experts: $N = 6$ and novices: $N = 6$) was small, therefore caution is needed when generalizing the results to the larger population of violinists. The activity of only three muscles was studied. Muscles in the neck, especially upper trapezius, probably also contribute to the bowing motion. The simple practice exercise performed by the subjects, with no specific instructions about tone and volume, does not present the same challenge as a concert piece played to the composer's specifications, although it did allow us to assess novice players along with experts.

Recommendations for future research: For a more accurate depiction of the muscular demands of the movement, activity from neck, shoulder and forearm muscles such as trapezius, sternocleidomastoid, middle and posterior deltoid, pectoralis major and the wrist and finger flexors and extensors should be studied. Looking at the left upper extremity would also be valuable, as there are reports in the literature of left arm pain which is as bad as, or worse than, that reported for the right side. Adding wrist kinematics to the analysis would be useful, since it appears that experts may use a slightly different wrist movement on the bowing arm, compared to novices. This different action may affect both performance and injury risk. Once the basic components of violin bowing have been identified, the next challenge is studying violinists playing an actual piece of music, with its tempo and therefore, velocity changes, bow pressure changes to achieve the required tone and bow manipulation for more advanced skills such as double stops. Future quantitative biomechanics research will be aided by obtaining more specific injury data on violinists, which includes the precise anatomical structures affected in the reported muscle strains, tendonitis, and ligament sprains. This would allow a closer link between the quantitative biomechanical measures and the injured structures. Understanding this should lead to injury prevention recommendations and possibly changes in the pedagogy of playing. This is already being done in work settings through ergonomic analyses, and has proven to be useful. Another line of research which could be pursued to achieve the goal of better understanding injury mechanisms is to assess movement patterns and muscle activity in injured violinists. It may also be possible to simulate injury by fatiguing or cooling a muscle group before playing, or by limiting joint ROM using restraints. This thesis has shown that quantitative biomechanical assessment

techniques can be successfully used with violinists, potentially opening the door to the same positive outcomes that have been achieved in the workplace.

FIGURE 1: Playing Posture/Position



(Szende & Nemessuri, 1971)

FIGURE 2: Motor Unit Action Potential Output

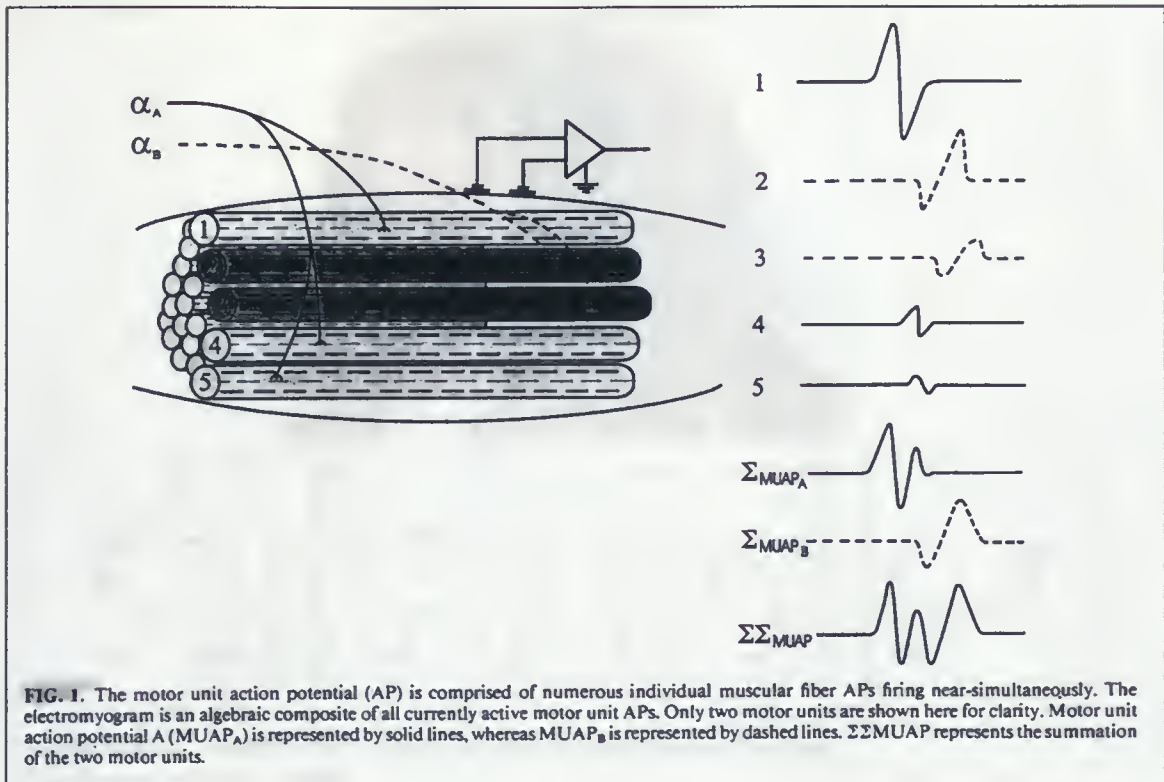
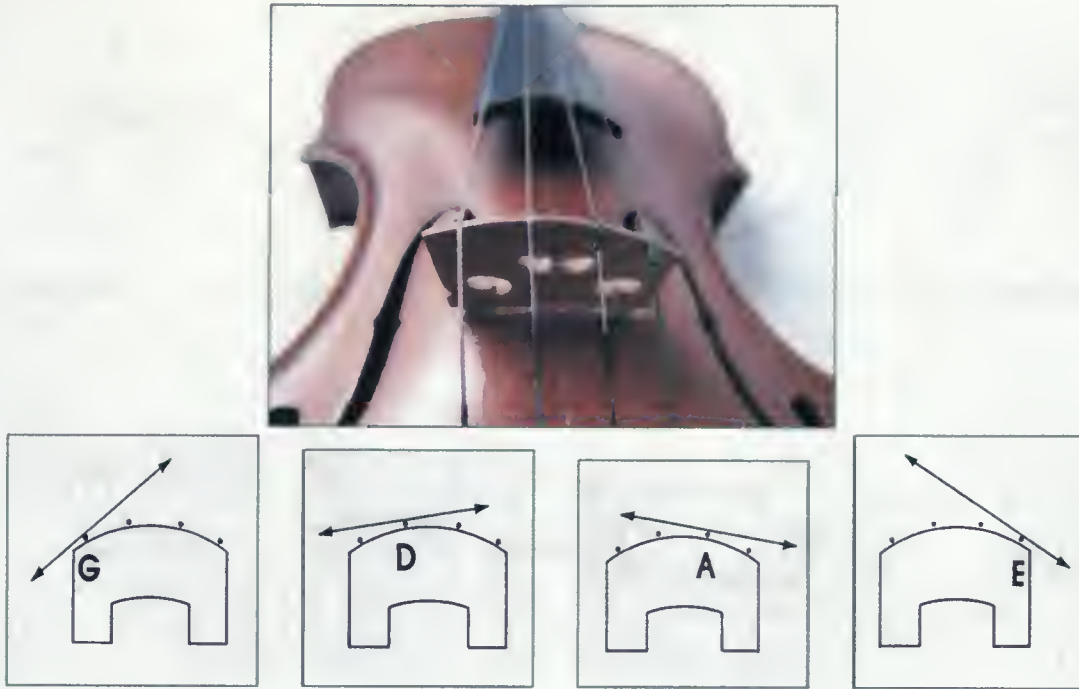


FIG. 1. The motor unit action potential (AP) is comprised of numerous individual muscular fiber APs firing near-simultaneously. The electromyogram is an algebraic composite of all currently active motor unit APs. Only two motor units are shown here for clarity. Motor unit action potential A (MUAP_A) is represented by solid lines, whereas MUAP_B is represented by dashed lines. $\Sigma \Sigma \text{MUAP}$ represents the summation of the two motor units.

(Kamen & Caldwell, 1996)

FIGURE 3: String Arrangement on Violin



String names, with the bow angle needed to play on each string (Anderson & Frost, 1985).



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FIGURE 4: Violin Playing Position Diagrams

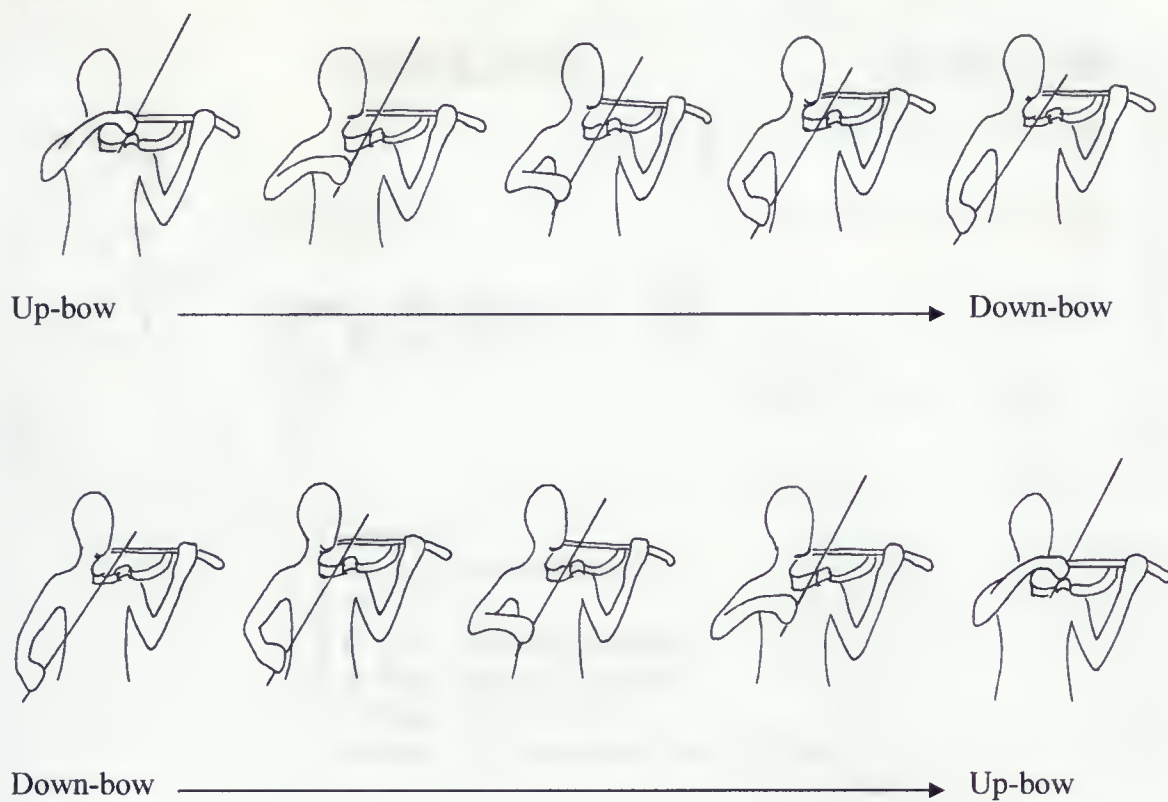
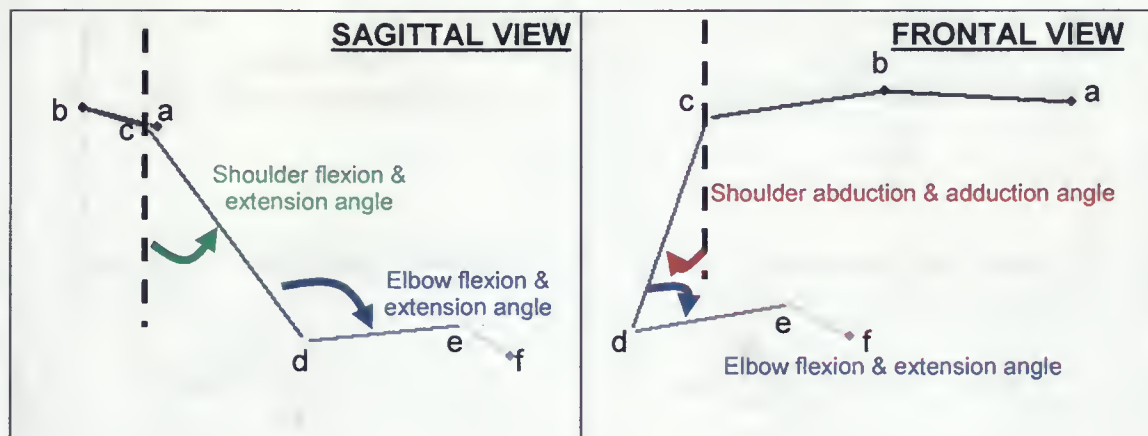


FIGURE 5a: Angle Output from Peak Motus (before defining the coordinate system)

**Legend:**

a: Left Acromion Process

b: C7

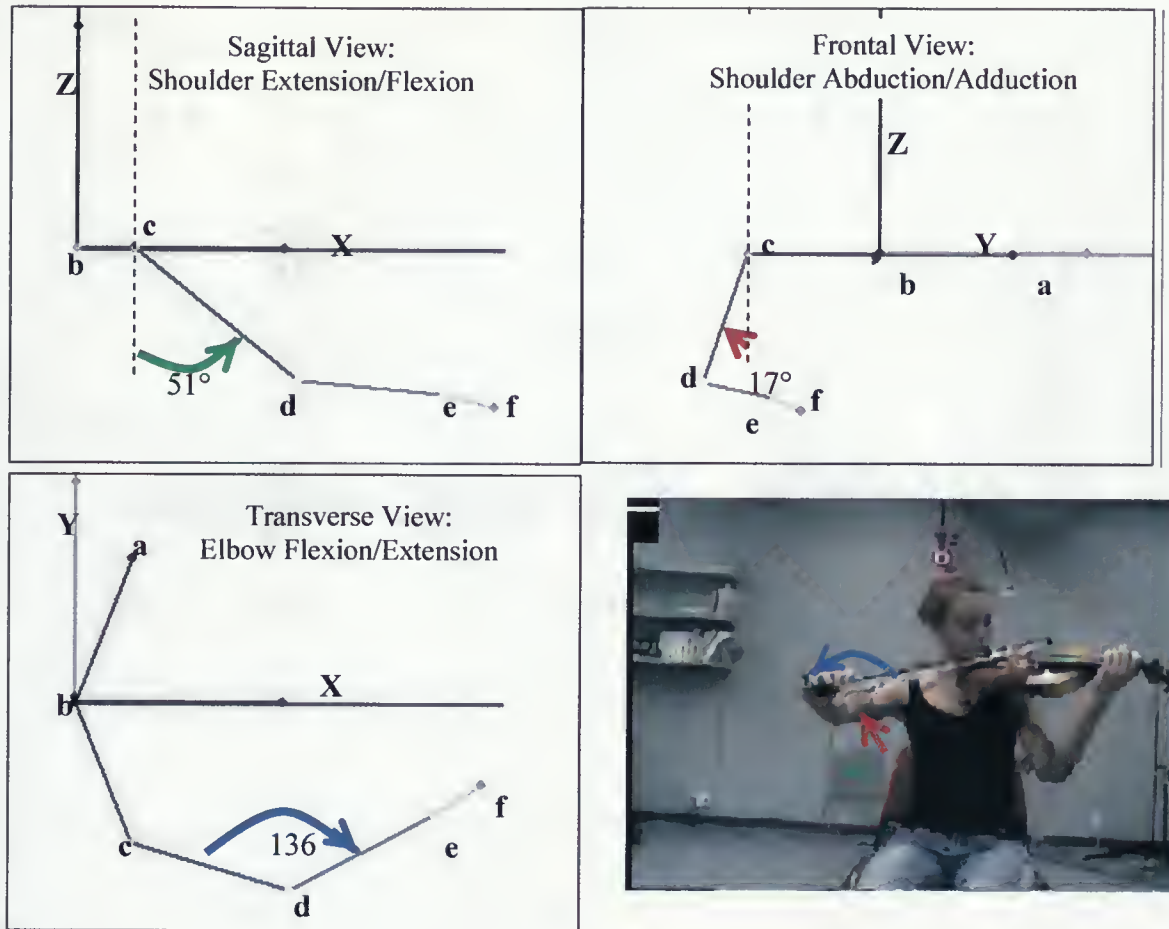
c: Right Acromion Process

d: Right Lateral Epicondyle

e: Right Ulnar Styloid

f: Right 5th Metacarpophalangeal Joint

FIGURE 5b: Transformed Angles



Shoulder and Elbow Angles during a Down-bow on E-String (arrows represent where the angles are calculated from)

Legend:

- a:** Left Acromion Process
- b:** C7 Vertebra
- c:** Right Acromion Process
- d:** Right Lateral Epicondyle
- e:** Right Ulnar Styloid
- f:** Right 5th Metacarpophalangeal Joint

X: X-axis

Y: Y-axis

Z: Z-axis

FIGURE 6: Matlab Output: Shoulder Flex/Ext. ROM with Triceps and Biceps EMG

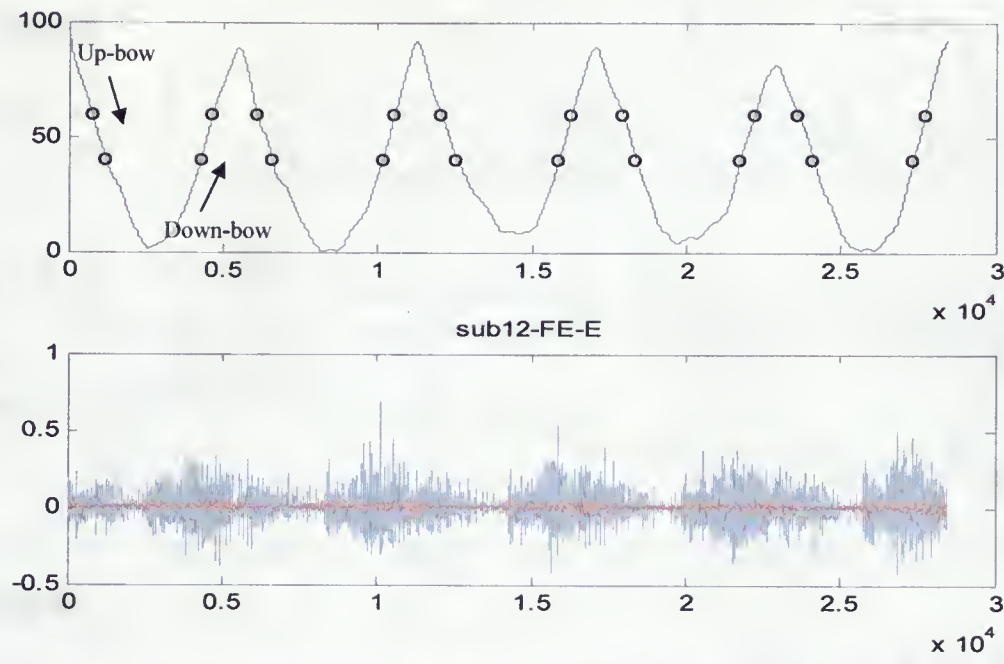
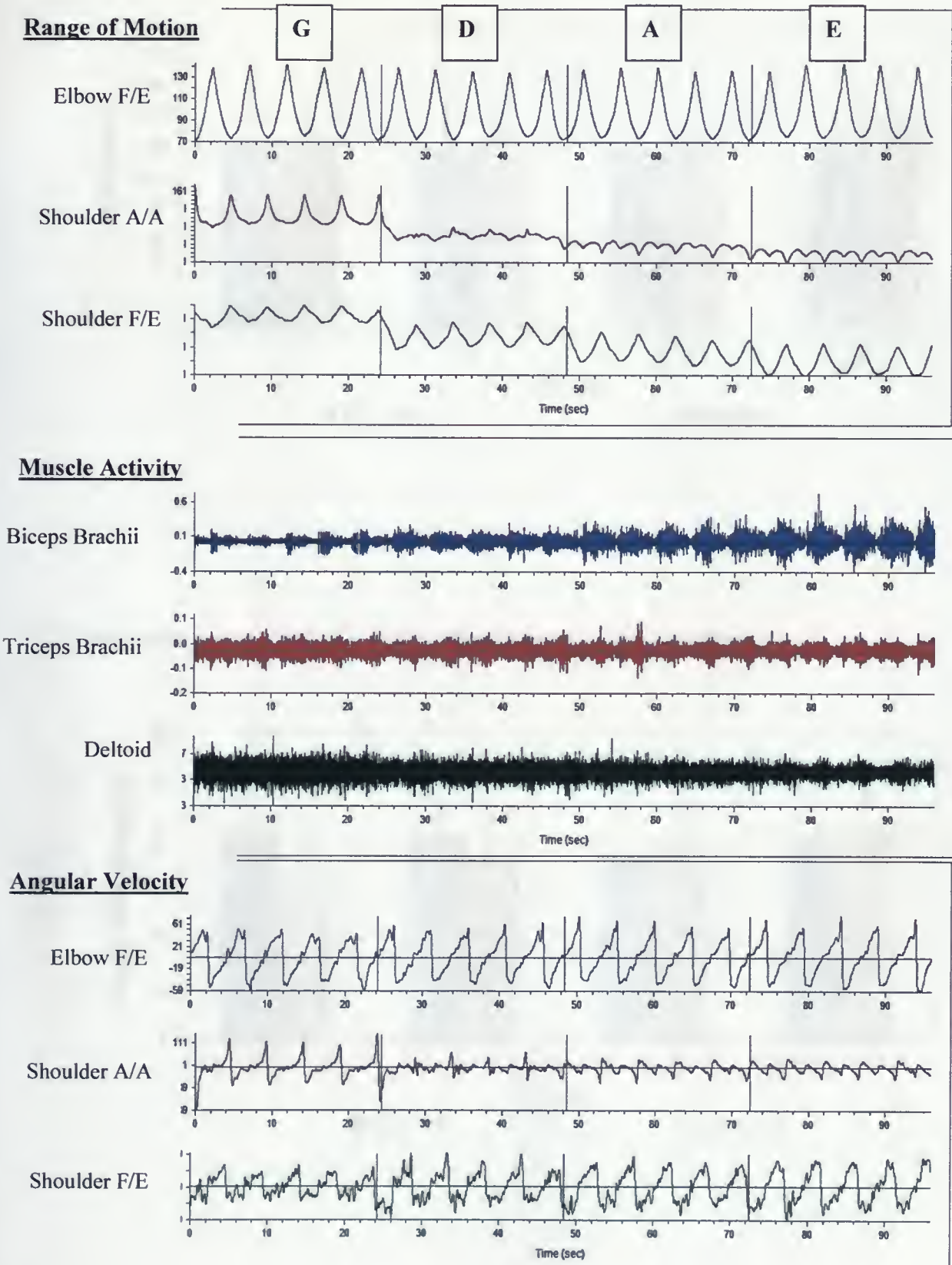


FIGURE 7: Kinematic Variables during the Playing Task for an Expert Violinist



1. The first part of the paper is devoted to the study of the properties of the function $f(x)$.

2. In the second part, we consider the case when the function $f(x)$ is continuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

3. In the third part, we consider the case when the function $f(x)$ is discontinuous and the measure μ is singular with respect to the Lebesgue measure.

4. In the fourth part, we consider the case when the function $f(x)$ is continuous and the measure μ is singular with respect to the Lebesgue measure.

5. In the fifth part, we consider the case when the function $f(x)$ is discontinuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

6. In the sixth part, we consider the case when the function $f(x)$ is continuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

7. In the seventh part, we consider the case when the function $f(x)$ is discontinuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

8. In the eighth part, we consider the case when the function $f(x)$ is continuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

9. In the ninth part, we consider the case when the function $f(x)$ is discontinuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

10. In the tenth part, we consider the case when the function $f(x)$ is continuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

11. In the eleventh part, we consider the case when the function $f(x)$ is discontinuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

12. In the twelfth part, we consider the case when the function $f(x)$ is continuous and the measure μ is absolutely continuous with respect to the Lebesgue measure.

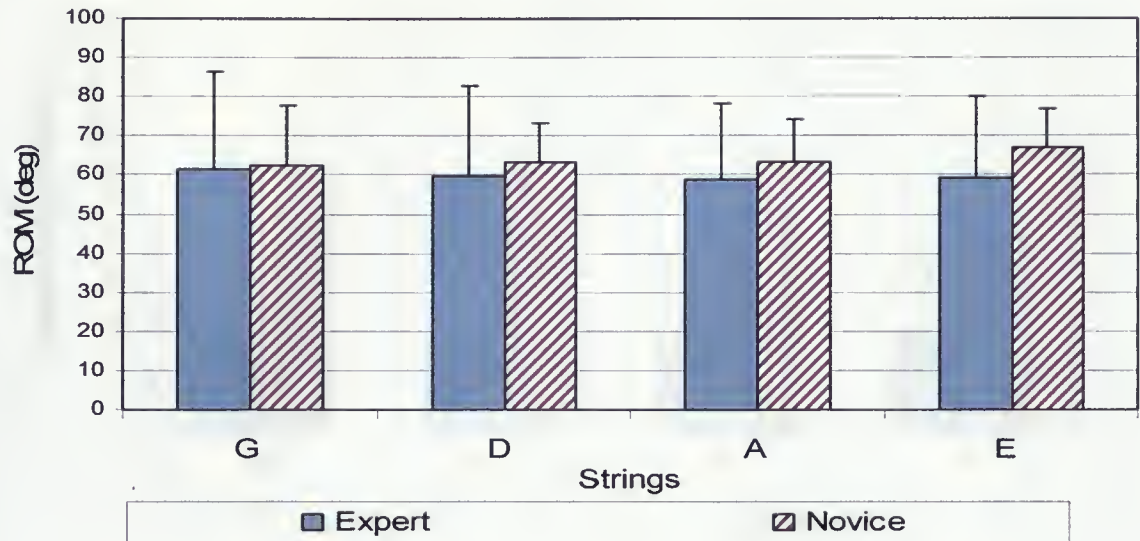
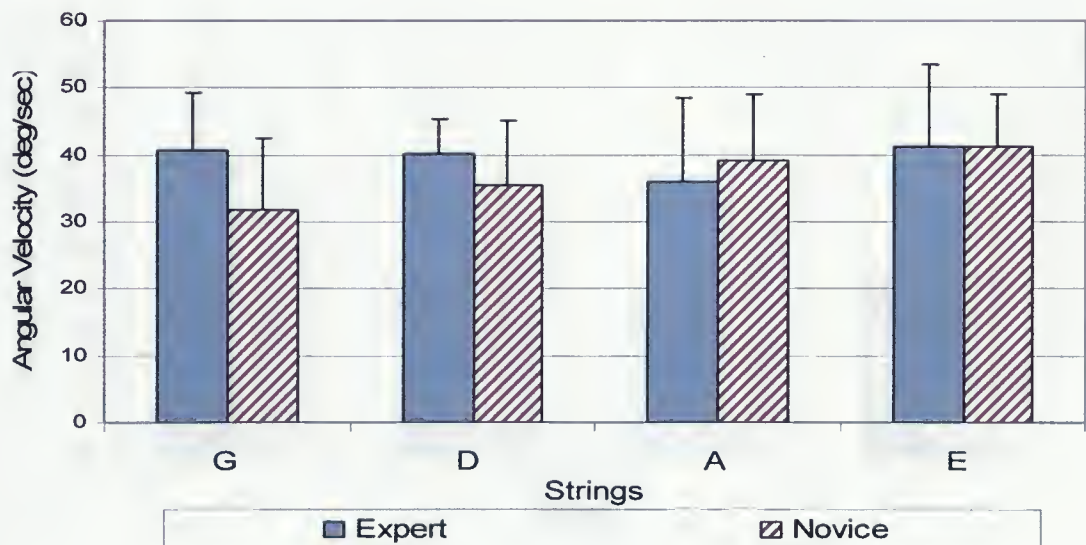
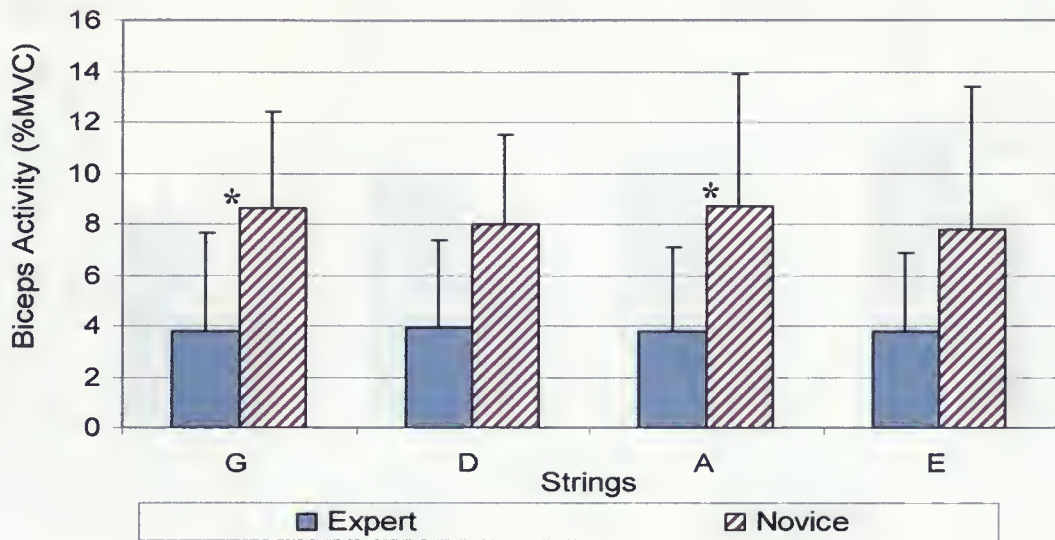
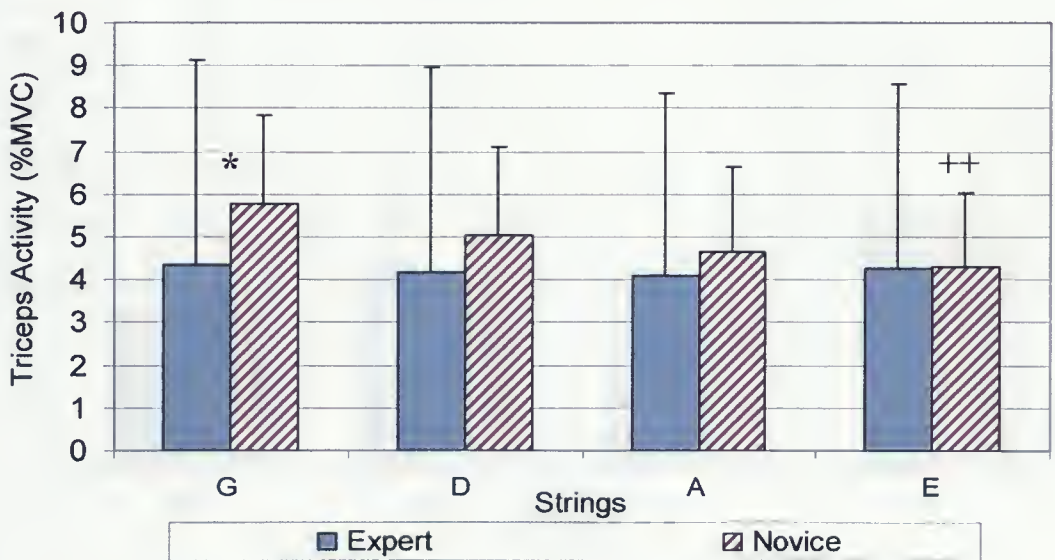
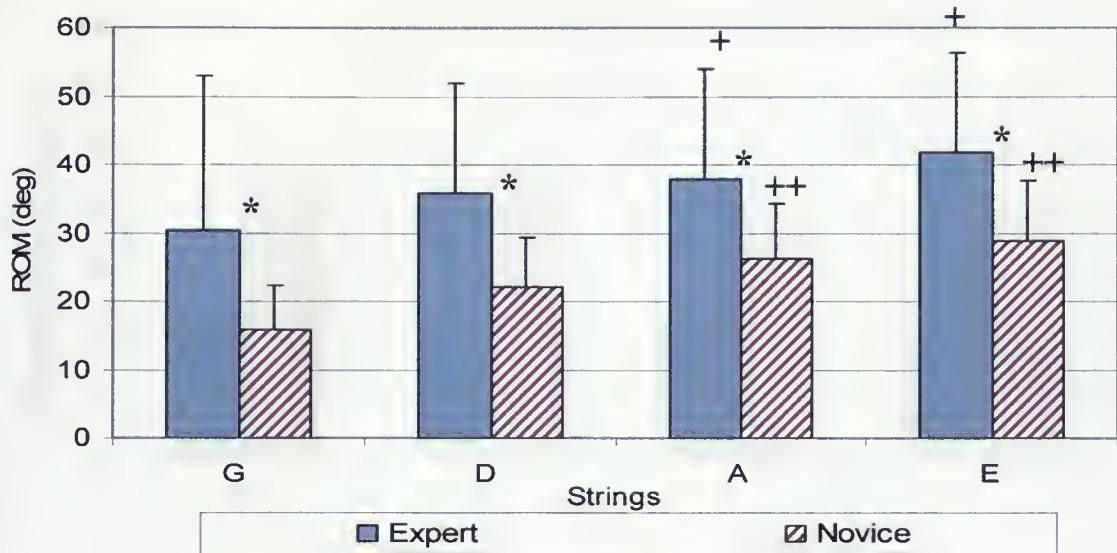
FIGURE 8: ROM during Elbow Flexion and Extension (mean \pm SD)FIGURE 9: Angular Velocity during Elbow Extension (mean \pm SD)

FIGURE 10: Biceps Activity during Elbow Extension (mean \pm SD)

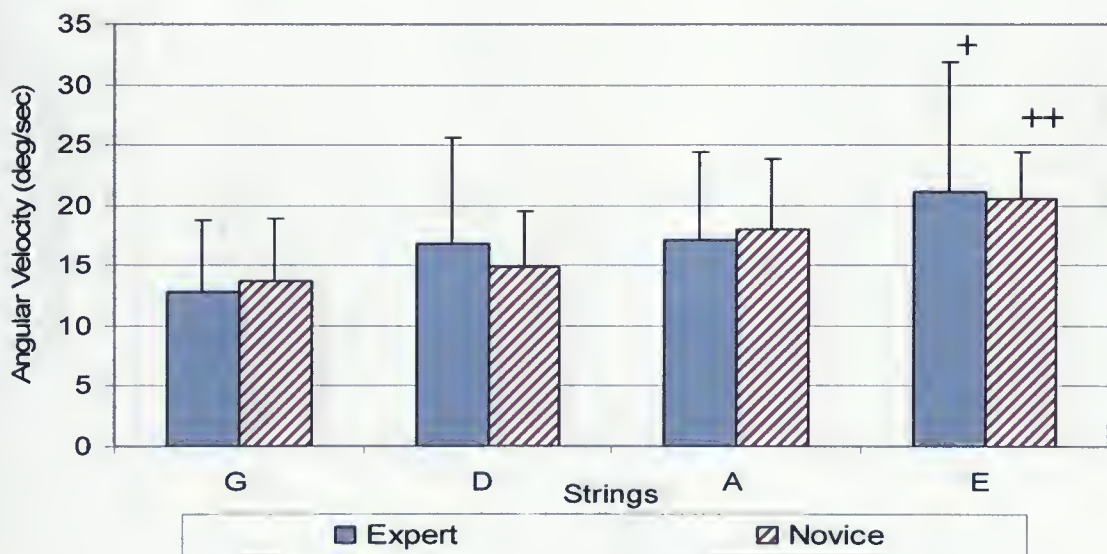
* Significantly different between experience groups (on specific string)

FIGURE 11: Triceps Activity during Elbow Extension (mean \pm SD)

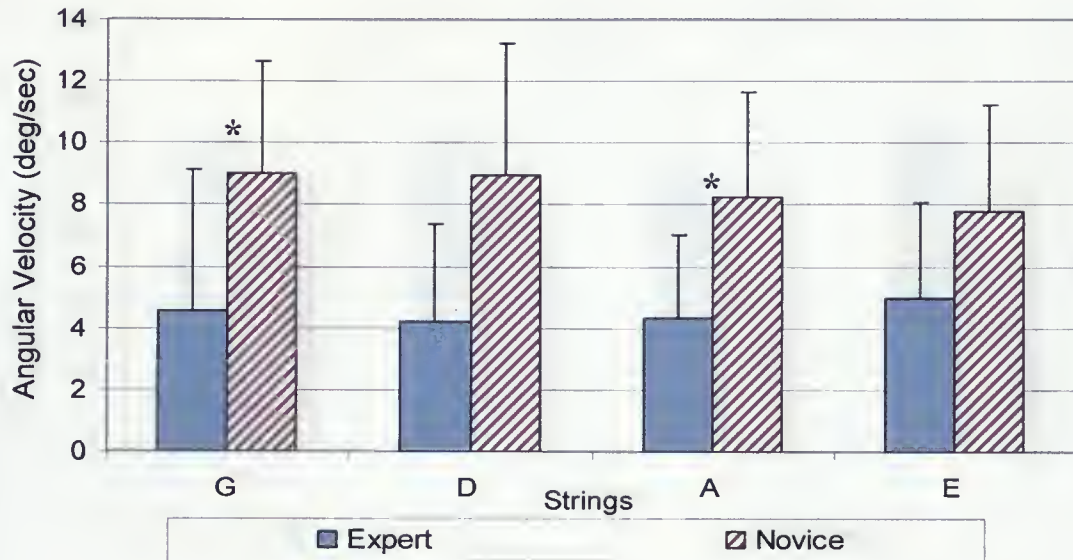
* Significantly different between experience groups (on specific string)
 ++ Significantly different from G string (in the novice group)

FIGURE 12: ROM during Shoulder Flexion and Extension (mean \pm SD)

- * Significantly different between experience groups (on specific string)
- + Significantly different from G string (in the expert group)
- ++ Significantly different from G string (in the novice group)

FIGURE 13: Angular Velocity during Shoulder Extension (mean \pm SD)

- + Significantly different from G string (in the expert group)
- ++ Significantly different from G string (in the novice group)

FIGURE 14: Biceps Activity during Shoulder Extension (mean \pm SD)

* Significantly different between experience groups (on specific string)

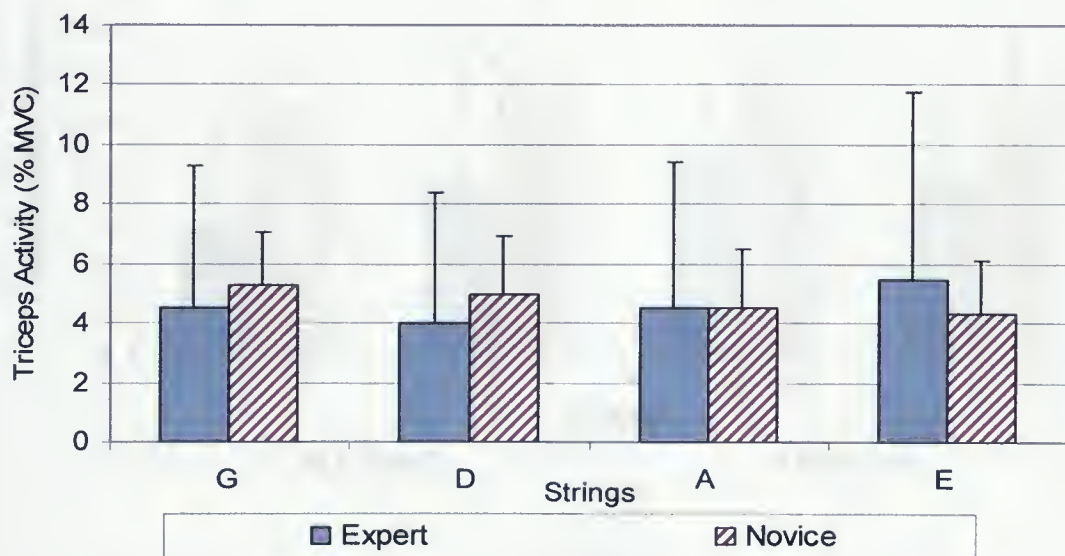
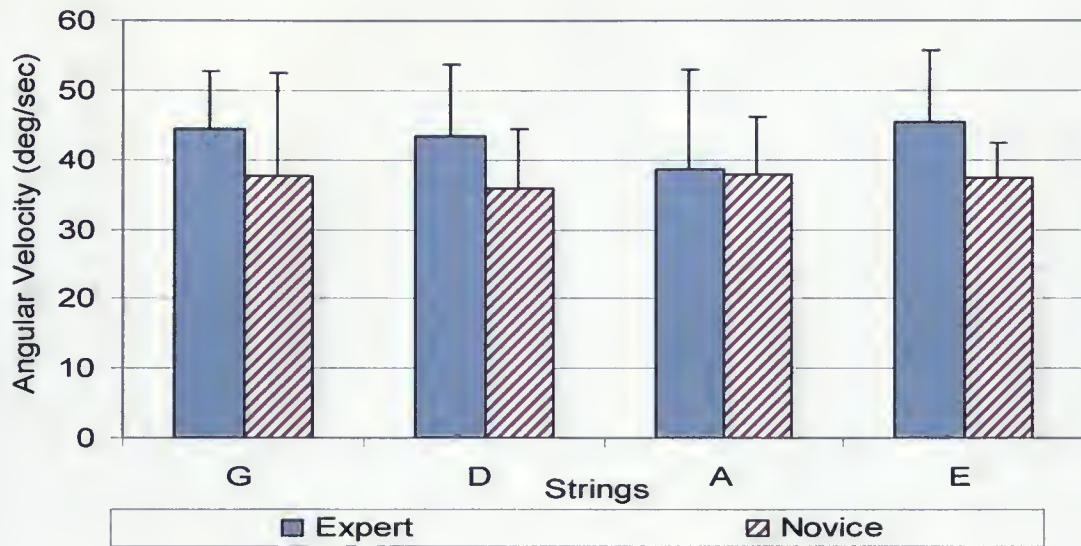
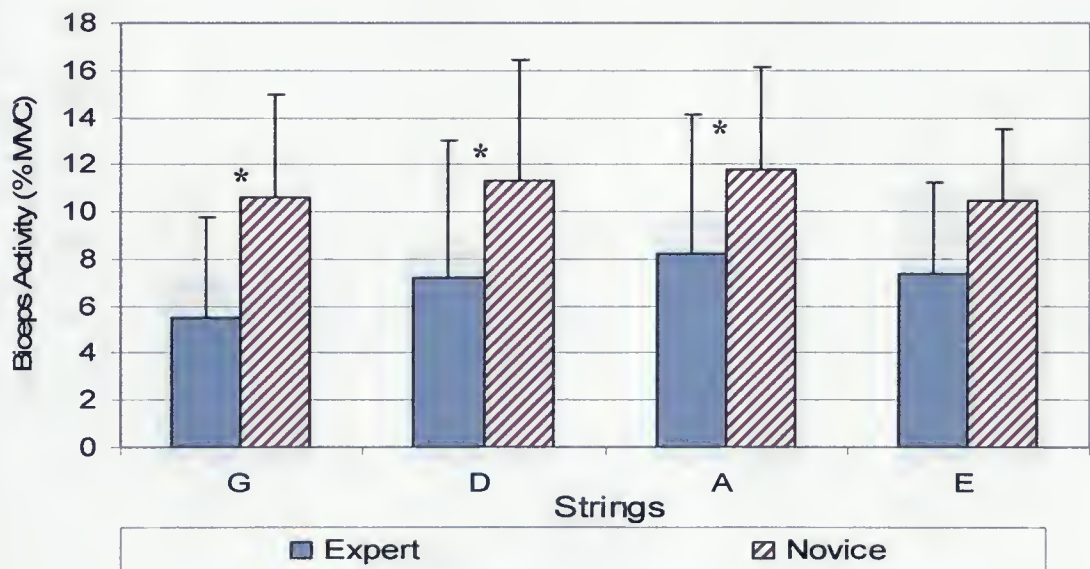
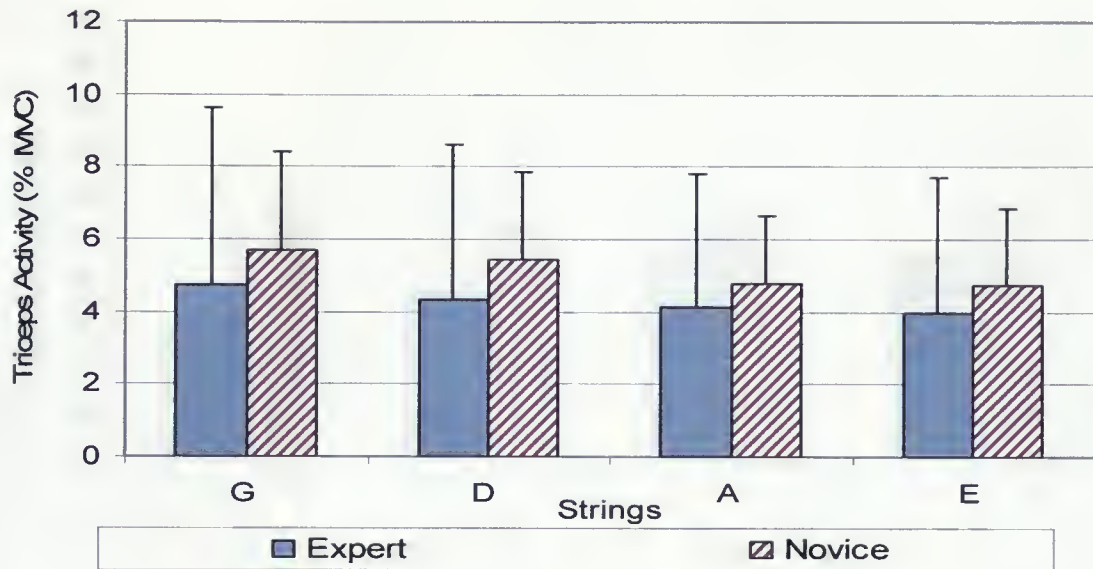
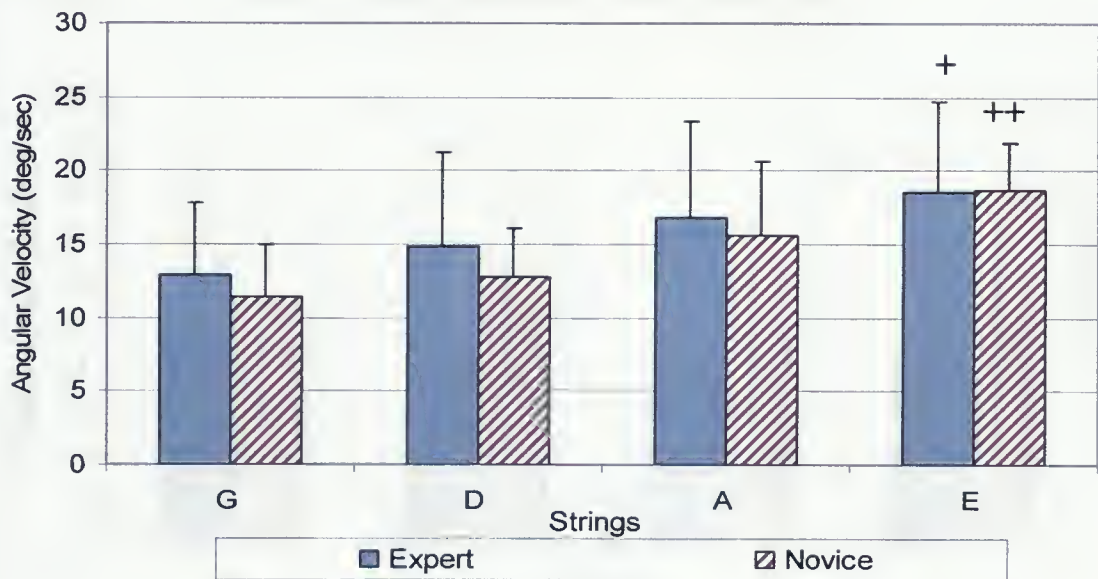
FIGURE 15: Triceps Activity during Shoulder Extension (mean \pm SD)

FIGURE 16: Angular Velocity during Elbow Flexion (mean \pm SD)FIGURE 17: Biceps Activity during Elbow Flexion (mean \pm SD)

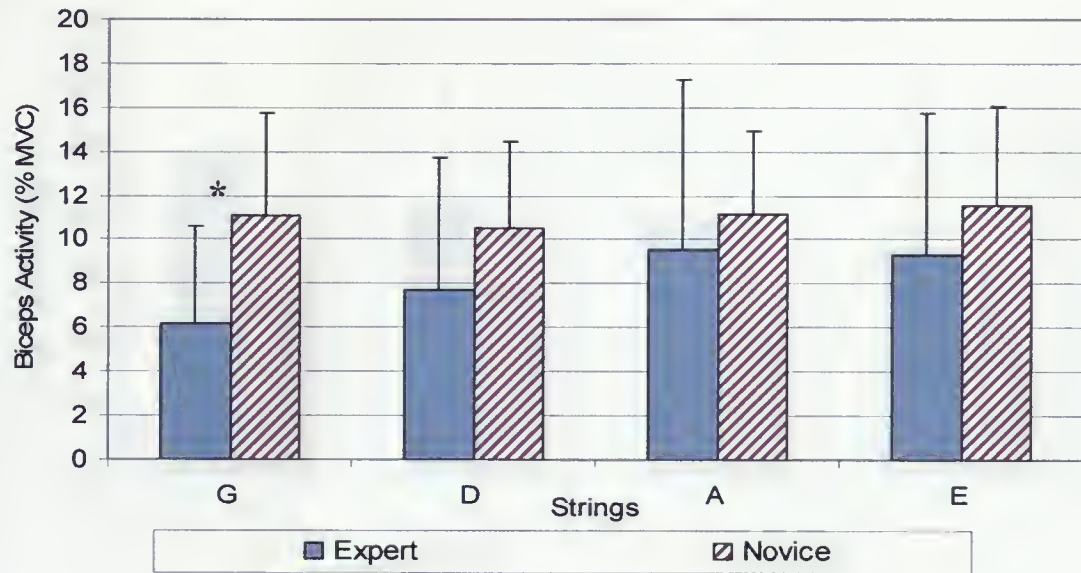
* Significantly different between experience groups (on specific string)

FIGURE 18: Triceps Activity during Elbow Flexion (mean \pm SD)FIGURE 19: Angular Velocity during Shoulder Flexion (mean \pm SD)

+ Significantly different from G string (in the expert group)

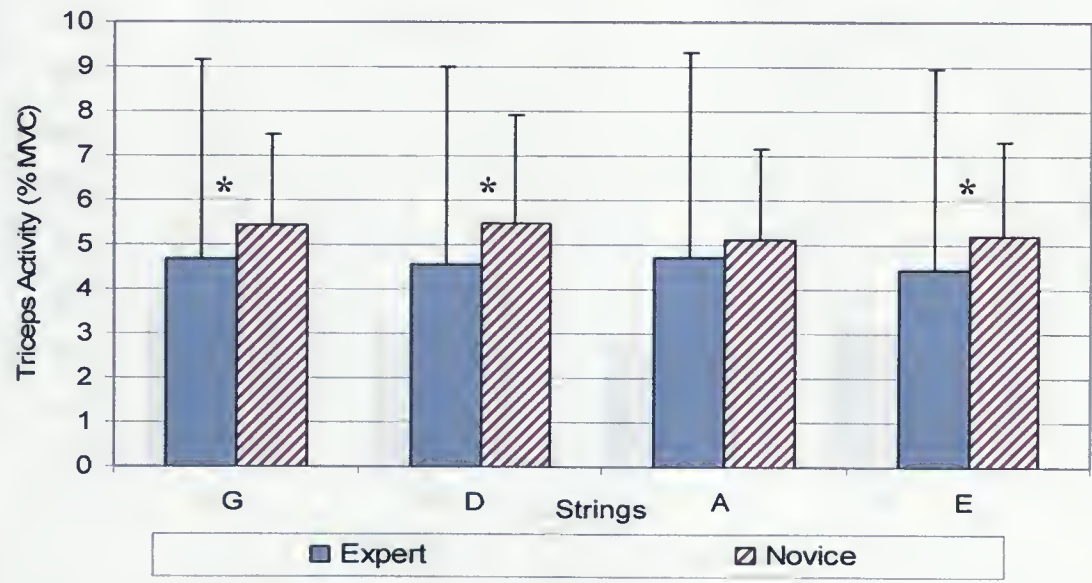
++ Significantly different from G string (in the novice group)

FIGURE 20: Biceps Activity during Shoulder Flexion (mean \pm SD)



* Significantly different between experience groups (on specific string)

FIGURE 21: Triceps Activity during Shoulder Flexion (mean \pm SD)



* Significantly different between experience groups (on specific string)

FIGURE 22: ROM during Shoulder Abduction (mean \pm SD)

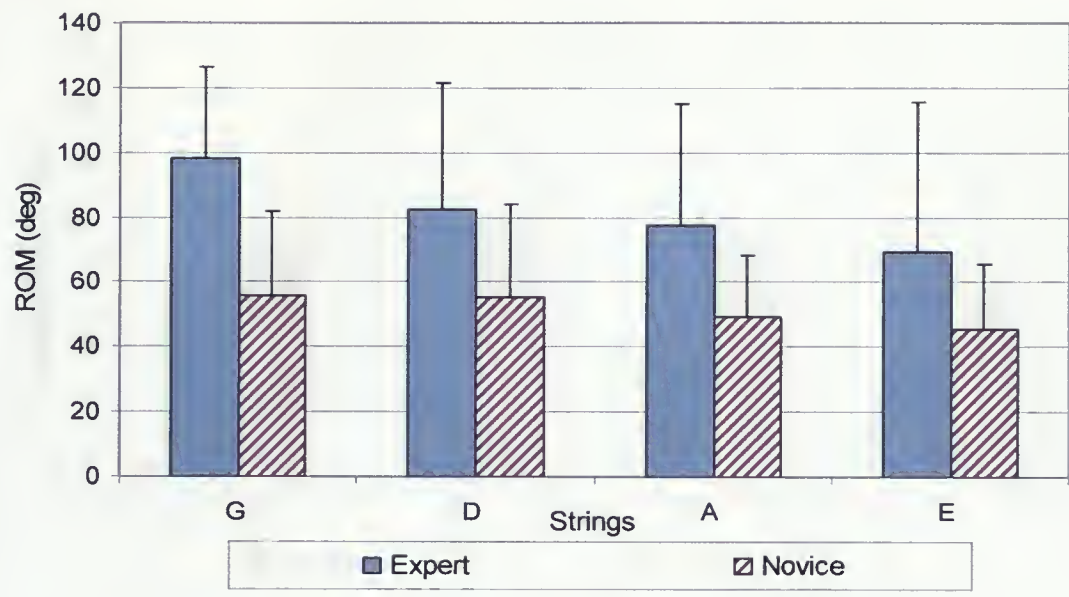


FIGURE 23: Angular Velocity during Shoulder Abduction (mean \pm SD)

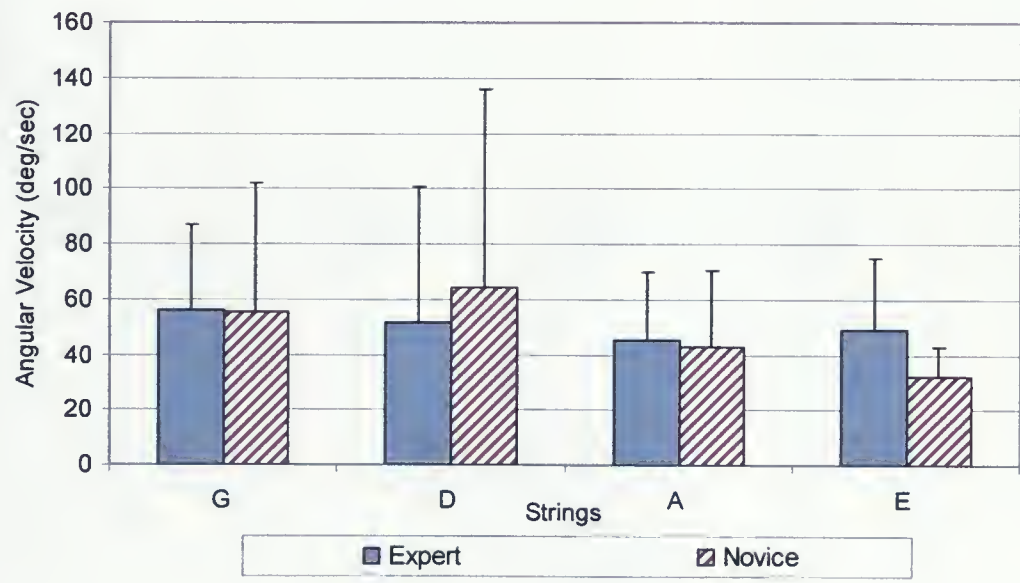
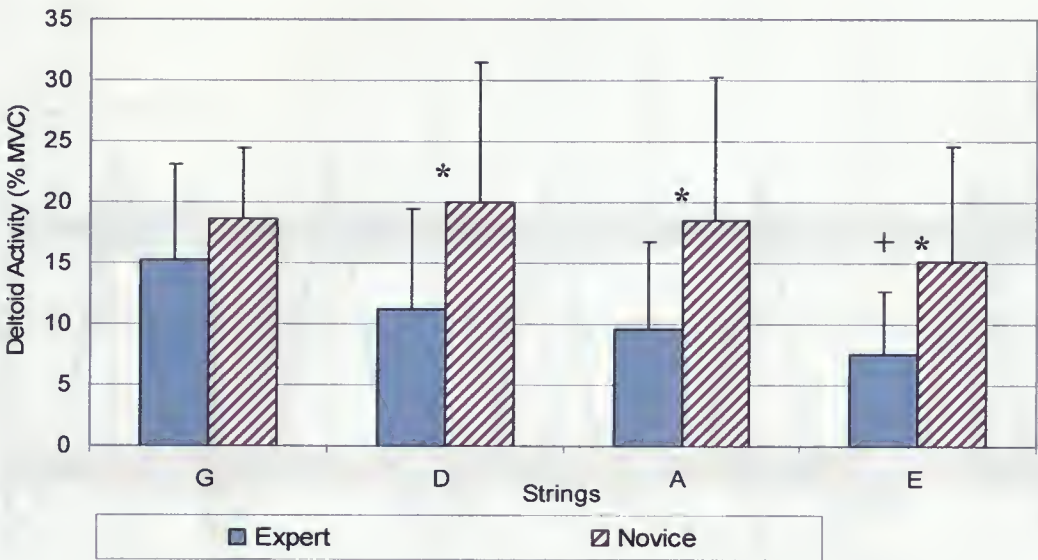


FIGURE 24: Deltoid Activity during Shoulder Abduction (mean \pm SD)



* Significantly different between experience groups (on specific string)
+ Significantly different from G string (in the expert group)

FIGURE 25a: Biceps and Triceps Muscle Activity of an Expert Violinist

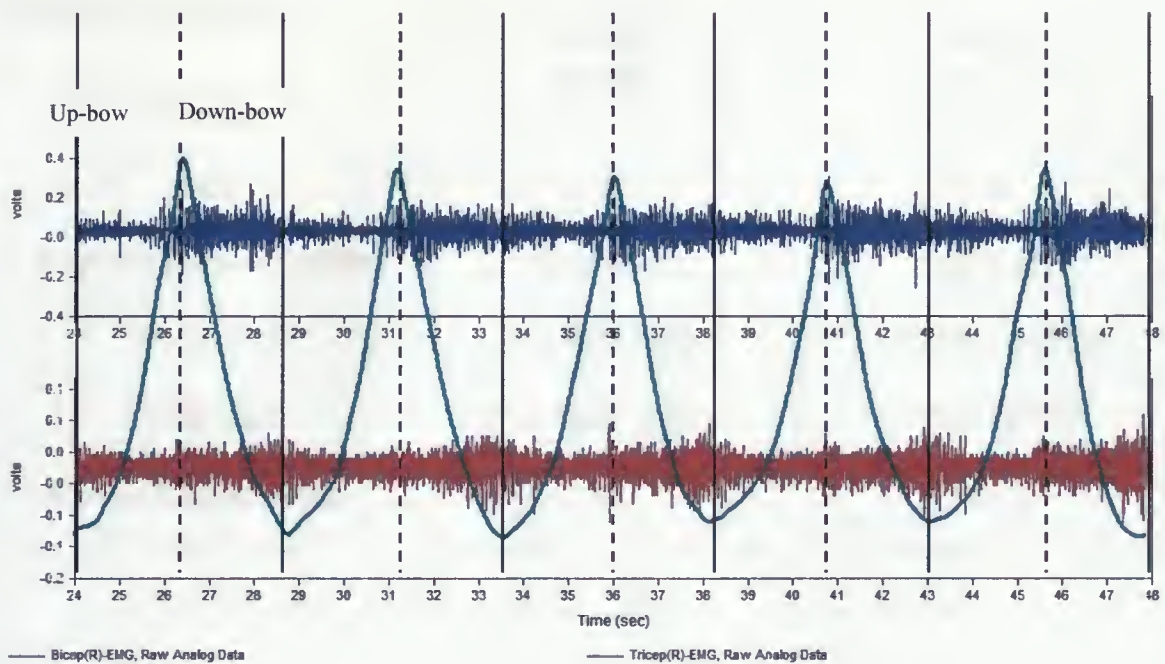


FIGURE 25b: Biceps and Triceps Muscle Activity of a Novice Violinist

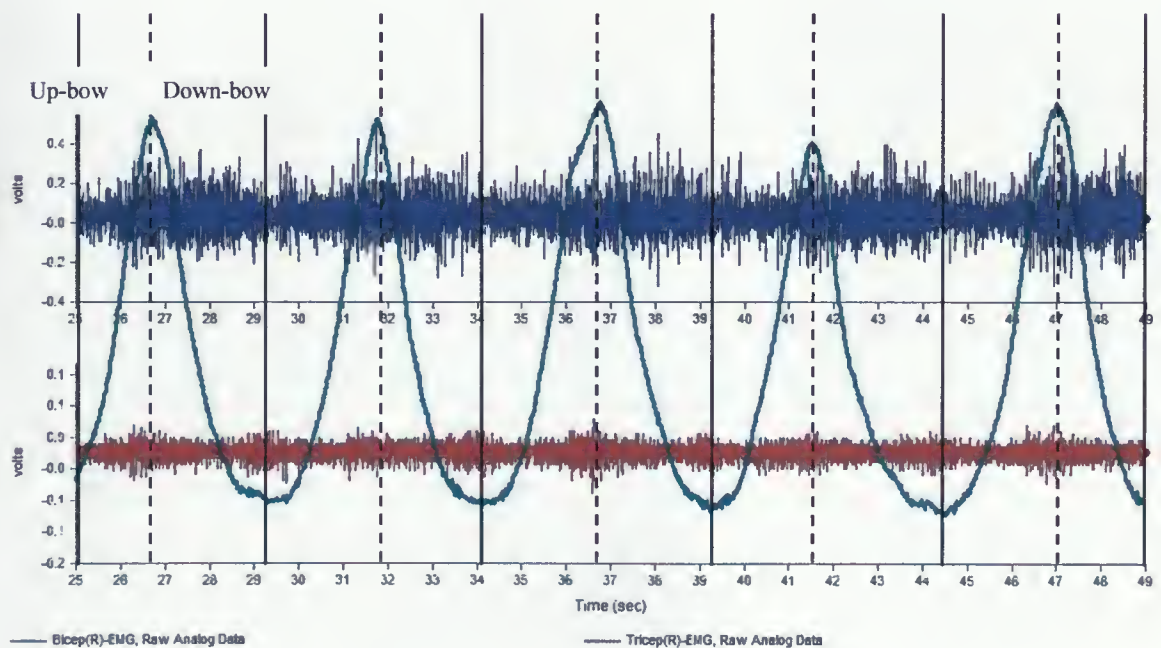




FIG. 10. Same as in Fig. 9, but for the difference in the 500-hPa geopotential height.



TABLE 1:

Subject Characteristics		
	Experts (n = 6)	Novices (n = 6)
Females	4	5
Males	2	1
Playing Experience (years)	14 (\pm 8.26)	4 (\pm 1.51)
Height (cm)	165.42 (\pm 10.7)	166.42 (\pm 10.7)
Mass (kg)	61.48 (\pm 18.4)	62.62 (\pm 6.7)
Sum of 4 Skinfolds (mm)	49.03	48.56

APPENDIX A: Questionnaire

Participant Questionnaire

Subject number: _____

Date of birth: _____

Playing experience:

How long have you played the violin? _____

How long have you taken violin lessons? _____

How often are your lessons? _____

Do you play in an orchestra or other group? _____

Practicing:

How often do you practice? _____

How long are your practice sessions? _____

Do you warm up before playing your violin? _____

If you warm up, **how** do you warm up?

physical warmup? _____

musical warmup? _____

Have you ever missed a performance, lesson or practice session because of pain related to playing your violin? _____

Do you currently have any physical conditions or injuries which would prevent you from playing your violin in your usual way? _____

Do you play any other instruments? _____ If so, which one(s)? _____

APPENDIX B: Information Sheet

Participant Information Sheet

This study is being conducted by Dr. Gail Frost (gail.frost@brocku.ca, (905) 688 5550 X4497) and Jenn Wales (jenn_wales@hotmail.com, (905) 227 3605) to establish a reliable method for assessing three-dimensional (3D) movement patterns and muscle activity patterns of the trunk and upper extremities in violinists as they play their instrument. By being able to look in detail at the movements and the muscles used to produce the movements, it may be possible to understand which patterns are associated with injury.

If you agree to participate in this study, you will be asked to attend one 90-minute session in the Biomechanics Lab at Brock University. This visit will include:

- a) assessment of height, weight and skinfold thickness
- b) completion of a questionnaire about your violin playing history (years of playing, weekly hours of practice, any significant injuries, etc.)
- c) playing two short exercises on your own instrument while motion and muscle activity data are collected

While playing the exercise, you will:

- a) wear stick-on electrodes on the skin over seven muscles in the back, arm and hand
- b) wear markers on bony landmarks to assess the amount of shoulder, elbow and wrist movement

To participate in this study, you will need to bring your own violin to play, and wear a sleeveless, snug-fitting top.

Your name will not appear in any report, publication or presentation resulting from this study. The data, with identifying information removed, will be retained indefinitely and will be securely stored in the investigator's office. Research assistants working on the study have signed a statement of confidentiality promising to uphold your anonymity and confidentiality. You will be informed of the results of the research through email or by letter when the study is finished.

It is important to understand that you are free to withdraw from the study at any time, without penalty, by letting the researcher know of your decision.

This study has been reviewed by and received approval from the Brock University Research Ethics Board (file # 04-005). Should you have any questions or concerns about your involvement in the study, you may contact the Research Ethics Officer at 905-688-5550 (ext. 3035).

You must provide your written consent to participate in this study. To indicate your consent, please complete the enclosed Consent Form and return it to the investigator. If you are 18 years of age or younger, please have a parent sign the Parental Consent

Form, after talking with the investigator and/or reading the Information Sheet and Participant Consent Form carefully.

If you have questions or are interested in participating in the study please contact:

Jenn Wales
(905) 227 3605
jenn_wales@hotmail.com

OR

Gail Frost, PhD
(905) 688 5550 X4497
gail.frost@brocku.ca

APPENDIX C: Consent Form

Participant Consent Form

I, _____ consent to participate in a research study designed to assess the movement and muscle activity patterns of violin players. I understand that the research has been reviewed and received ethics approval through the Brock University Research Ethics Board file # 04-005. The investigator, Dr. Gail Frost (gail.frost@brocku.ca, 905 688 5550 X4497) has explained the purposes of the research, as well as the procedures to be followed, and has also explained that there are no known risks involved with participating in the study. I am also aware that there may not be any direct benefits from participating.

I have been told that my presence is required in the Biomechanics Laboratory at Brock University for a 90-minute session, and that if I have any questions about the research, I am encouraged to ask. I am aware that the data collected in this study will be kept confidential, and that I will not be identified, should the data be published in any form. I also understand that I am not obligated to participate in this study, and that I am free to withdraw from it at any time, without penalty.

Plans and Procedures

After giving my consent, the investigator and I will set up a convenient time when I will report to the Biomechanics Lab at Brock for the experimental session. Once again the investigator will review the procedures and purposes of the study as outlined below, and answer any questions I may have. As a participant, I will complete a brief questionnaire, designed to provide information about my violin playing history, practice schedule and any playing-related injuries I may have incurred. I understand that the following anthropometric data will then be collected: height, weight and sum of skinfolds at four sites (suprailiac, subscapular, triceps, biceps). Nine reflective markers for motion tracking will be placed on my back, shoulder, arm and hand. After the skin is prepared, surface EMG electrodes will be applied to the skin over seven muscles on my trunk, arm and hand to record muscle activation patterns. I will then contract each of the muscles to be studied for three seconds as hard as I can, in order to provide a reference for comparison with the EMG data collected during the playing task. The investigator has explained that the electrodes will measure the electrical activity of the muscles, similar to the electrodes that measure the activity of the heart during an electrocardiogram. The playing task that I will perform will be moderately slow legato bowing on one string at a time, to a metronome setting of four beats per bow at 100 beats per minute. The left hand will play on the third finger in first position, using a natural vibrato pattern. Data will be recorded for 12 bowing cycles on each string.

I understand that my name will not appear in any report, publication or presentation resulting from this study. The data, with identifying information removed, will be retained indefinitely and will be securely stored in the investigator's office. I will be informed of the results of the research through email or by letter when the study is finished.

I agree to participate under the conditions that I have read, and I understand all of the relevant information. I understand that I am entitled to ask questions at any point of the

study and in the future. I have been advised to keep a copy of the Informed Consent Form for my records so that I may refer back to it at any time.

_____ Name (print)	_____ Signature	_____ Date
-----------------------	--------------------	---------------

_____ Witness (print)	_____ Signature	_____ Date
--------------------------	--------------------	---------------

_____ I have explained the nature and outlined the parameters of this study to
_____ and believe that he/she understands what is involved.

_____ Investigator (print)	_____ Signature	_____ Date
-------------------------------	--------------------	---------------

If you have any questions or concerns, please contact:

Investigator:
Gail Frost, PhD
(905) 688-5550 x.4497
gail.frost@brocku.ca

Research Ethics Officer:
(905) 688-5550 X3035
REB file #04-005

APPENDIX E: Kinematic and EMG Data in Table Form

Range of Motion (degrees) during Elbow Flexion and Extension (mean + SD)

	G	D	A	E
Expert	61.69 ± 24.95	59.74 ± 22.84	58.87 ± 19.39	59.40 ± 20.83
Novice	62.33 ± 15.61	63.19 ± 9.96	63.17 ± 10.89	66.99 ± 9.82

Angular Velocity (degrees/sec) during Elbow Extension (mean + SD)

	G	D	A	E
Expert	40.63 ± 8.77	40.14 ± 5.31	35.89 ± 12.68	41.20 ± 12.19
Novice	31.95 ± 10.55	35.44 ± 9.72	39.04 ± 9.93	41.11 ± 7.92

Biceps Activity (% MVC) during Elbow Extension (mean + SD)

	G	D	A	E
Expert	3.81 ± 3.85	3.94 ± 3.41	3.82 ± 3.25	3.82 ± 3.07
Novice	8.61 ± 3.80	7.99 ± 3.49	8.70 ± 5.21	7.81 ± 5.56

Triceps Activity (% MVC) during Elbow Extension (mean + SD)

	G	D	A	E
Expert	4.37 ± 4.77	4.18 ± 4.77	4.10 ± 4.26	4.27 ± 4.32
Novice	5.76 ± 2.10	5.05 ± 2.06	4.65 ± 1.99	4.30 ± 1.72

Range of Motion (degrees) during Shoulder Flexion and Extension (mean + SD)

	G	D	A	E
Expert	30.43 ± 22.49	35.95 ± 16.02	37.94 ± 16.06	41.86 ± 14.38
Novice	15.88 ± 6.54	22.11 ± 7.18	26.21 ± 8.19	28.78 ± 8.86

Angular Velocity (degrees/sec) during Shoulder Extension (mean + SD)

	G	D	A	E
Expert	12.78 ± 5.92	16.81 ± 8.88	17.10 ± 7.35	21.09 ± 10.71
Novice	13.67 ± 5.28	14.83 ± 4.69	18.06 ± 5.76	20.48 ± 3.95

Biceps Activity (%MVC) during Shoulder Extension (mean + SD)

	G	D	A	E
Expert	4.57 ± 4.57	4.23 ± 3.13	4.33 ± 2.71	4.96 ± 3.15
Novice	9.01 ± 3.65	8.97 ± 4.25	8.25 ± 3.39	7.78 ± 3.47

Triceps Activity (%MVC) during Shoulder Extension (mean + SD)

	G	D	A	E
Expert	4.49 ± 4.79	4.00 ± 4.37	4.54 ± 4.88	5.50 ± 6.25
Novice	5.28 ± 1.81	4.99 ± 1.93	4.54 ± 1.95	4.31 ± 1.83

Angular Velocity (degrees/sec) during Elbow Flexion (mean + SD)

	G	D	A	E
Expert	44.48 ± 8.25	43.54 ± 10.28	38.73 ± 14.31	45.49 ± 10.12
Novice	37.69 ± 14.87	35.83 ± 8.71	37.98 ± 8.21	37.50 ± 4.86

Biceps Activity (% MVC) during Elbow Flexion (mean + SD)

	G	D	A	E
Expert	5.50 ± 4.25	7.20 ± 5.85	8.21 ± 5.89	7.40 ± 3.87
Novice	10.65 ± 4.32	11.34 ± 5.09	11.76 ± 4.40	10.45 ± 3.04

Triceps Activity (%MVC) during Elbow Flexion (mean + SD)

	G	D	A	E
Expert	4.73 ± 4.90	4.31 ± 4.32	4.14 ± 3.69	3.99 ± 3.74
Novice	5.69 ± 2.72	5.44 ± 2.41	4.77 ± 1.90	4.72 ± 2.15

Angular Velocity (degrees/sec) during Shoulder Flexion (mean + SD)

	G	D	A	E
Expert	12.89 ± 4.90	14.82 ± 6.46	16.86 ± 6.45	18.61 ± 6.05
Novice	11.42 ± 3.53	12.84 ± 3.30	15.67 ± 4.97	18.75 ± 3.16

Biceps Activity (%MVC) during Shoulder Flexion (mean + SD)

	G	D	A	E
Expert	6.16 ± 4.41	7.71 ± 5.99	9.53 ± 7.77	9.29 ± 6.48
Novice	11.12 ± 4.64	10.49 ± 3.97	11.16 ± 3.80	11.58 ± 4.52

Triceps Activity (%MVC) during Shoulder Flexion (mean + SD)

	G	D	A	E
Expert	4.66 ± 4.48	4.57 ± 4.43	4.72 ± 4.59	4.43 ± 4.53
Novice	5.45 ± 2.05	5.47 ± 2.45	5.13 ± 2.02	5.21 ± 2.12

Range of Motion (degrees) during Shoulder Abduction and Adduction (mean + SD)

	G	D	A	E
Expert	98.30 ± 28.33	82.71 ± 38.87	77.83 ± 37.21	69.71 ± 45.66
Novice	55.87 ± 25.99	55.39 ± 28.89	49.58 ± 18.88	45.40 ± 20.06

Angular Velocity (degrees/sec) during Shoulder Abduction (mean + SD)

	G	D	A	E
Expert	55.80 ± 31.37	51.96 ± 48.60	45.37 ± 24.50	48.89 ± 26.10
Novice	55.28 ± 46.62	64.02 ± 71.84	42.67 ± 27.58	32.09 ± 10.69

Deltoid Activity (%MVC) during Shoulder Abduction (mean + SD)

	G	D	A	E
Expert	15.32 ± 7.77	11.21 ± 8.19	9.65 ± 7.09	7.52 ± 5.21
Novice	18.60 ± 5.88	20.02 ± 11.41	18.54 ± 11.77	15.20 ± 9.35

		Max ShA/A (Shoulder Abduction)	Min ShA/A (Shoulder Adduction)	Max ShF/E (Shoulder Flexion)	Min ShF/E (Shoulder Extension)	Max EF/E (Elbow Extension)	Min EF/E (Elbow Flexion)
Expert	G	176.1	77.9	110.2	79.7	133.0	71.3
	D	130.7	45.6	102.8	66.8	129.3	69.5
	A	104.9	32.3	98.2	60.2	127.2	68.3
	E	77.6	12.9	94.6	52.7	127.4	68.0
Novice	G	119.0	63.1	102.3	86.4	125.2	62.9
	D	102.6	47.2	92.0	69.9	127.4	64.2
	A	76.3	26.7	86.6	60.4	128.1	65.0
	E	57.2	11.8	77.2	48.4	131.3	64.3

APPENDIX F: Statistical Output

Variable	Statistically significant difference across strings for EXPERTS	Statistically significant difference across strings for NOVICES	Statistically significant difference BETWEEN EXPERT and NOVICES on each string	Table Number
ROM Elbow	-	-	-	8
Angular Velocity Elbow Extension	-	-	-	9
Biceps Elbow Extension	-	-	G (0.013760) A (0.011770)	10
Triceps Elbow Extension	-	G E (0.007671)	G (0.012431)	11
ROM Shoulder Flexion/Extension	G A (.040271) G E (.000538)	G A (.001733) G E (.000198)	G (.000147) D (.000157) A (.000412) E (.000185)	12
Angular Velocity Shoulder Extension	G E (0.000388)	G E (0.040730)	-	13
Biceps Shoulder Extension	-	-	G (0.030308) D (0.017140)	14
Triceps Shoulder Extension	-	-	-	15
Angular Velocity Elbow Flexion	-	-	-	16
Biceps Elbow Flexion	-	-	G (0.000954) D (0.010509) A (0.041358)	17
Triceps Elbow Flexion	-	-	-	18
Angular Velocity Shoulder Flexion	G E (0.005415)	G E (0.004171)	-	19
Biceps Shoulder Flexion	-	-	G (0.005933)	20

Triceps	-	-	G (0.019734)	21
Shoulder Flexion			D (0.005030)	
			E (0.020776)	
ROM	-	-	-	22
Shoulder				
Abduction/Adduction				
Angular Velocity	-	-	-	23
Shoulder Abduction				
Deltoid	G E (0.026652)	-	D (0.008672)	24
Shoulder Abduction			A (0.007855)	
			E (0.030601)	
Elbow	-	-	-	
Minimum				
Elbow	-		-	
Maximum				
Shoulder	G D (.013250)	G D (.000868)	-	
Flexion/Extension	G A (.000196)	G A (.000142)		
Minimum	G E (.000142)	G E (.000142)		
	D E (.005251)	A E (.026570)		
		D E (.000151)		
Shoulder	G and A	G D (0.002644)	G (0.038945)	
Flexion/Extension	(0.000478)	G A (0.000144)	D (0.001627)	
Maximum	G and E	G E (0.000142)	A (0.000706)	
	(0.000144)	D E (0.000150)	E (0.000142)	
	D and E	A E (0.007572)		
	(0.026130)			
Shoulder	G D (.020774)	G A (.006558)	-	
Abduction/Adduction	G A (.000523)	G E (.000196)		
Minimum	G E (.000142)	D E (.008598)		
	D E (.018987)			
Shoulder	G A (.008487)	G E (.031684)	-	
Abduction/Adduction	G E (.000259)			
Maximum				

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