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The Effects of Body Orientation and Humeral Elevation Angle on Shoulder Muscle Activity and Shoulder Joint Position Sense

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Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

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The Effects of Body Tilt and Humeral elevation angle on Shoulder Muscle Activity and Shoulder Joint Position Sense

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The Faculty of
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Abstract

The purpose of this study was to determine the effects of body tilt on shoulder muscle activity and repositioning accuracy during humeral elevation to three positions in the sagittal plane (70, 90 and 110 degrees). Thirty eight subjects underwent testing in an unconstrained joint position sense task. Kinematics were measured with a magnetic tracking device while muscle activation was measured with surface electromyography. The joint position sense task consisted of subjects moving their arms to a predetermined positing in space with the help of visual feedback from a head mounted display interfaced with the magnetic tracking device. Subjects were then asked to reproduce the presented shoulder position in the absence of visual feedback. The protocol was performed under two tilts: upright and back 90 degrees from vertical. This allowed for the comparison of joint position sense at the same elevation angles but different levels of shoulder muscle activation by altering the orientation of the subjects in the gravitational field. When comparing these two tilts we found that subjects matched with greater accuracy and precision at 90 and 110 degrees of elevation when they were upright ($p < 0.05$). We also found that anterior deltoid muscle activity was significantly greater at all three elevation angles in the upright condition. This data, when taken together support the hypothesis that unconstrained shoulder joint position sense is enhanced with increased muscular activation levels.

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Chapter I

The Problem and Its Scope

Introduction

Movements in both athletic and daily environments require signals coming from our moving bodies so we can determine the position of our limbs in space while adapting and reacting to rapidly changing conditions. These signals come from mechanoreceptors located in the periphery which have been termed proprioceptors. The term 'proprioception' was coined by Sherrington in 1906 who said that "In muscular receptivity we see the body itself acting as a stimulus to its own receptors—the proprioceptors". Traditionally proprioceptors have been restricted to those receptors concerned with conscious sensations which include the sense of limb position and movement, the sense of tension or force, the sense of effort and the sense of balance (Proske & Gandevia, 2012). The sense of limb position and movement are paired together and have been termed kinesthesia (Proske, 2006) which is primarily determined by skeletal muscle spindles (Proske & Gandevia, 2009; Proske, 2006).

The stability of our joints relies heavily on feedback loops involving mechanoreceptors in the muscles (Banks, Hulliger, Saed, & Stacey, 2009; Banks, 2006; Swash & Fox, 1972), skin (Johansson & Vallbo, 1979; Kennedy & Inglis, 2002) and joints (Gerhardt et al., 2012; Steinbeck et al., 2003). The integrated of these mechanoreceptors with the central nervous system (CNS), the degree of bony congruity and the integrity of capsuloligamentous supporting structures is critical to joint stability (Nyland, Caborn, & Johnson, 1998). In the shoulder specifically, where a large amount of mobility comes at a detriment to stability, proper communication between mechanoreceptors in the periphery and the CNS is crucial to the maintenance of accurate position sense. Joint position sense (JPS) is determined in the CNS from the combination of peripheral information from joint receptors, muscle spindles and Golgi tendon organs (Riemann & Lephart, 2002b) as well as central mechanisms such as motor commands and the sense of effort (Allen, Ansems, & Proske, 2006; Gandevia, Smith, Crawford, Proske, & Taylor, 2006; Smith, Crawford, Proske, Taylor, & Gandevia, 2009; Voss, Ingram, Haggard, & Wolpert, 2006; L. D. Walsh, Gandevia, & Taylor, 2010; Winter, Allen, & Proske, 2005).

Historically, both active and passive matching paradigms have been used to delineate the multitude of mechanisms involved in JPS. Two of the most common methods for studying JPS in the orthopedic literature are the threshold to detection of passive motion (TTDPM) and the reproduction of passive positioning (RPP). In TTDPM test the joint is passively rotated from a starting position with the use of a mechanical device, and the blindfolded subject indicates when they first detect motion, usually by pushing a button on a trigger that stops the machine. The passive nature of the procedure is thought to selectively stimulate mechanoreceptors in the joint structures (Lephart, Pincivero, & Rozzi, 1998). In RPP testing, the joint is rotated, usually passively, through a range of motion to a specific target angle. The subject holds the target angle for a period of time before returning to the start position. The subject then actively or passively attempts to replicate the presented angle. In passive modes the joint will be moved through the range of motion by a mechanical apparatus and the blindfolded subject indicates when they believe they have accurately replicated the presented angle, usually by pressing a button on a trigger that stops the testing apparatus. This testing method is thought to assess the function of mechanoreceptors in the joint as well as Golgi tendon organs and muscle spindles (Lephart et al., 1998). Proprioceptive acuity tested using TTDPM and RPP has been shown to be diminished in those people suffering from joint injury (Lephart, Warner, Borsa, & Fu, 1994; Machner et al., 2003; Warner, Lephart, & Fu, 1996). In order to better understand how active segments perform in matching tasks, researchers started to use bilateral active matching tasks where one limb is placed in a specific position (called the reference limb) that the subject than attempts to match with their other, free limb (indicator limb). This type of test is typically isolated to a single joint such as the wrist, knee, elbow or shoulder. More recently active unconstrained repositioning tests (AUR) have been used to study JPS in a more dynamic and functional environment.

Unconstrained active paradigms allow subjects to move their limbs in all three dimensions without altering or restricting their natural range of motion (ROM). These types of tests allow for measurements of JPS in a much more functional setting. Using this method, transducers are attached to the segments of interest and the subject is placed in a small magnetic field so three dimensional kinematics of the involved segments can be recorded. This method has been found to be a valid and non-invasive means of determining kinematics in the upper extremities (Karduna, McClure, Michener, & Sennett, 2001).

Unconstrained unilateral active repositioning paradigms have shown that JPS acuity increases with arm elevation up to 90°, and decreases thereafter (Suprak, Osternig, van Donkelaar, & Karduna, 2006). One hypothesis surrounding this observation implicates the role of gravity in altering the torque on the joint due to the change in the external moment observed with arm elevation up to 90 degrees. Furthermore, the addition of weight during a similar unconstrained matching task improved matching accuracy, which is indicative of both muscle activation levels as well as motor command signals improving JPS acuity (Suprak, Osternig, van Donkelaar, & Karduna, 2007). However, when Chapman, Suprak and Karduna (2009) attempted to uncouple joint angle from joint torque they found that matching based on elevation angle demonstrated no significant difference, while matching based on torques did result in differences. This finding implies that elevation angle at the shoulder may play a more important role in modulating JPS than joint toque. However, the extent to which both joint torque and shoulder elevation angle contribute to JPS remains to be determined. Therefore, it was the goal of this study to further examine the relative contribution of body orientation and joint angle on JPS acuity by having subjects match in a vertical and supine body positions such that the same relative angles for the arm are tested in each orientation. In this way, joint angle with respect to the thorax remained the same while joint torques were altered.

Purpose of the Study

To study the effects of shoulder elevation (joint angle) and body orientation (upright and supine) on shoulder muscle activity and repositioning errors (absolute and variable).

Hypotheses

Based on observations from the Chapman article and the effects of progressive humeral elevation with respects to JPS matching accuracy, our hypothesis is that segment angle will play a larger role in determining JPS acuity than muscle activation levels with humeral elevation up to 90 degrees. Experimentally, therefore JPS acuity will be the most accurate at 90 degrees of humeral elevation in both the seated and supine positions, regardless of the torque due to gravity.

Significance of the Study

By helping to establish if JPS is determined more by the level of muscle activation or joint angle, coaches and practitioners will be better able to design rehabilitation/training programs for athletic and injured populations by selecting positions that optimize JPS acuity and resistive torque.

Limitations of the Study

1. These results apply only to healthy college aged subjects so caution should be used when extrapolating the results to other populations.
2. Limited positions were tested to avoid subject fatigue so extrapolating these results to all shoulder positions should be done with care.
3. A controlled environment was used where vision was occluded. In the real world people almost always have access to visual input which can alter the performance of the proprioceptive system. This limits the external validity of our study.

Definition of Terms

Proprioceptor: Receptor concerned with conscious sensations, including the senses of limb position and movement, the sense of tension or force, the sense of effort, and the sense of balance (Proske & Gandevia, 2012).

Mechanoreceptor: A sense organ that responds to mechanical stimulation/displacement (Crapse & Sommer, 2008a).

Muscle spindle: A stretch-sensitive mechanoreceptor that lies within human skeletal muscle whose primary role is to provide information pertaining to muscle length and speed of movement (Hunt, 1990)

Golgi tendon organ: A contraction-sensitive mechanoreceptor that is mostly found at points of attachment of muscle fibers to tendinous tissue, including deep intramuscular tendons or aponeuroses whose primary role is to provide information to the CNS pertaining to muscle tension (Jami, 1992).

Joint position sense: The ability to evaluate subjectively the position of a limb in space (Grigg, Finerman, & Riley, 1973)

Kinesthesia: The combined sensations of limb position and movement (Proske, 2006).

Sense of effort: A signal of central origin that provides positional information on body segments based on the effort required to maintain the position (Winter et al., 2005)

Motor command: A centrally generated signal that is monotonically related to motoneuronal output to the muscle (L. D. Walsh et al., 2010).

Efference copy: A copy of the efferent motor command issued to an effector — to the sensory pathway (Crapse & Sommer, 2008a).

Reafference: Those inputs that inevitably result from an animal's own movements (Crapse & Sommer, 2008a).

Exafference: Input that results from occurrences in the environment (Crapse & Sommer, 2008a).

Thixotropy: The dependence of a muscle's passive mechanical property on its previous history of contraction and length changes (Proske, Morgan, & Gregory, 1993).

Population code: The combined proprioceptive signal coming from the whole set of muscle, skin, joint and tendon afferents surrounding a joint that are used collectively to determine the spatial position of the joint (Edith Ribot-Ciscar, Bergenheim, Albert, & Roll, 2003).

Chapter II

Review of Literature

Introduction

Joint position sense is critical to both daily activities as well as those of a more athletic nature. How exactly is it that people are able to control the number of fingers they have pointed up behind their backs or determine the location of their feet while walking down stairs in the dark? Such questions have driven the research in this field since the 17th century. The current theory is that JPS is calculated in the CNS with the help of mechanoreceptors in the periphery as well as central mechanisms lying within the brain itself. While our understanding of JPS has come a long way since Sherrington published his influential text book chapter on "The muscular sense", there is still much that remains a mystery.

The body of literature and all of its subtopics surrounding JPS are varied and many. It is for this reason that this review will focus mainly on those most well studied and supported mechanisms without delving into the more abstract and highly specific areas. The review will be separated into two parts. The first will deal with the peripheral systems involved in JPS. Here we will discuss the roll of joint receptors, Golgi tendon organs, muscle spindles and intrafusal muscle thixotropy in position matching errors and how muscle vibration has implicated the muscle spindle as being the primary kinesthetic sensor. Finally, we will discuss how information coming from the group of mechanoreceptors surrounding a joint contributes to a population code and how active and passive matching paradigms elucidate the functional aspects of JPS. The second part will deal with those systems and mechanisms lying within the CNS.

Review of the Pertinent Literature

Afferent information coming from mechanoreceptors located in the peripheral nervous system is crucial to the central computation of joint position sense. Here we will discuss the primary peripheral components and mechanisms that contribute to JPS.

Joint receptors. Joint receptors play an integral role in position sense. The two most common types of mechanoreceptors found in joints are Ruffini nerve endings and Pacinian corpuscles. Ruffini nerve endings are low threshold sensory receptors located within the joint capsule. They are stretch sensitive and thought to be stimulated by capsular stress associated with end ranges of motion (Voight, Hardin, Blackburn, Tippett, & Canner, 1996). These receptors are considered slow adapting, which means that they generate a continuous and steady discharge of electrical activity when presented with a continuous stimulus (Riemann & Lephart, 2002a). Pacinian corpuscles are low threshold, rapidly adapting mechanoreceptors located in the joint capsule as well as the synovial membrane and fibrosum layer. They are stimulated by tissue deformation resulting from rapid changes in direction and velocity in the initial and end stages of a joints range of motion (Voight et al., 1996).

People with recurrent traumatic anterior shoulder instability and degenerative osteoarthritis of the knee display deficits in position sense, mainly in the end ranges of motion (Lephart et al., 1994; Skinner, Barrack, Cook, & Haddad, 1984). Lephart, Warner, Borso & Fu (1994) studied the effects of surgical repair on passive position sense at the glenohumeral joint and found that the deficits accompanying the unstable shoulder were removed after surgical repair. Traumatic shoulder instability is almost always accompanied by damage to the labroligamentous structures (Jana et al., 2012). These structures are a rich source of free nerve endings and slow adapting Ruffinian receptors (Steinbeck et al., 2003). It follows that any damage to these structures, as in the case of shoulder dislocation and osteoarthritis, will alter the control of JPS and movement. Along with joint receptors, cutaneous mechanoreceptors have been shown to influence position sense (Collins, 2005). Collins, Refshauge, Todd & Gandevia (2005) showed that stretch of the skin surrounding joints magnified the movement illusion induced by vibration of the muscle spindles in the prime movers by 1.4 to 1.5 times compared to vibration alone. Muscle vibration has been shown to target and stimulate the primary endings of muscle spindles, causing subjects to perceive movement in a static limb (Goodwin, McCloskey, & Matthews, 1972). This phenomenon has been termed the vibration illusion. The augmentation of the vibration illusion following skin stretch suggests that cutaneous mechanoreceptors contribute to kinesthesia. However, both joint and skin receptors do not appear to be the primary receptors of kinesthesia and the main support of this hypothesis comes from observations of persistent senses of position and movement after joint replacement. Osteoarthritis of the knee is found to produce position sense deficits, repair of the joint by total arthroplasty does not resolve the deficits (Skinner et al., 1984). While the total knee arthroplasty group performed significantly worse than age-matched controls, the JPS acuity of operated and non-operated legs was essentially identical. The authors concluded that the decline in sensation was due to the disease process and not to further damage by total knee arthroplasty. Similar results have been shown for total hip replacement (Grigg et al., 1973). In both cases, position and movement sense remain intact in patients who have had removal of capsular and ligamentous structures. The previous observations imply that joint receptors are not the primary determiners of JPS which has led to the study of other mechanoreceptors, mainly the Golgi tendon organ and the muscle spindle.

Golgi tendon organs. Golgi tendon organs are contraction-sensitive mechanoreceptors of mammalian skeletal muscles innervated by fast-conducting Ib afferent fibers. They are encapsulated corpuscles whose main component is an elongated fascicle of collagen bundles attached at one end to the individual tendons of a small fascicle of muscle fibers, while the other end is in continuity with the whole muscle tendon or aponeurosis (Jami, 1992). Each receptor is thus placed "in series" with a group of muscle fibers. Assessment of muscle tension is considered to be the primary task of tendon organs. However, tendon organs are not equally sensitive to passive and active tensions. They display a very low threshold and an appreciable dynamic sensitivity when tested with their adequate stimulus. They are mostly found at points of attachment of muscle fibers to tendinous tissue, including deep intramuscular tendons or aponeuroses. This widespread distribution allows for the monitoring of contractions in every portion of the muscle so that the activity of virtually every motor unit in a muscle can be signaled by at least one tendon organ. The contraction of muscle fibers attached in series with a tendon organ provides the specific stimulus for the receptor because it strains the collagenous bundle which entails deformation of sensory terminals (Jami, 1992; Moore, 1984).

Muscle spindles. Muscle spindles are given their name from the fusiform appearance produced by the increase in their diameter in the equatorial region. They consist of a bundle of small intrafusal muscle fibers of three different types (called nuclear bag1, nuclear bag2 and nuclear chain fibers) surrounded, except in the polar regions, by a capsule that lies in parallel with extrafusal muscle fiber (Hunt, 1990). Muscle spindles are primarily stretch receptors and are unique to other mechanoreceptors in that they are equipped with motor neurons from the central nervous system (CNS) enabling them to modify the response of their endings to a particular stimulus (Allen, Ansems, & Proske, 2007; Hospod, Aimonetti, Roll, & Ribot-Ciscar, 2007; E. Ribot-Ciscar, Hospod, Roll, & Aimonetti, 2008; Swash & Fox, 1972). Intrafusal muscle fibers consist of a central, non-contractile region encircled by a connective tissue capsule and polar contractile regions, capable of sarcomere shortening upon stimulation, much like extrafusal muscle fibers. Nuclear bag fibers are named for their more rounded appearance in their central region while nuclear chain fibers have a more cylindrical shape. The central, or sensory region is subdivided into the equatorial region (occupied by the primary endings of the large and fast conducting Ia afferents) and the juxtaequatorial region (occupied by the secondary endings of the smaller and more slowly conducting group II afferents) which is also referred to as the polar region (Hulliger, 1984). The motor innervation of the spindle is distributed between γ- and β-motoneurons. γ-motonerurons can further be subdivided into static and dynamic types, according to whether they decrease or increase the dynamic response of Ia afferents to large stretches (Hunt, 1990). Muscle spindles are primarily stretch receptors. They are also hypothesized to be the primary receptor of kinesthesia as supported by the thixotropy and vibration studies that follow.

Thixotropy. Thixotropy is the dependence of a muscle's passive mechanical property on its previous history of contraction and length changes. It arises from the presence of stable cross bridge formation between actin and myosin in the sarcomeres of resting muscles, including both intra- and extrafusal muscle fibers (Proske & Morgan, 1999). The spontaneous formation of these long lasting stable cross bridges results in an initial rise in tension at the onset of stretch in a passive muscle called the short range elastic component (SREC). This rise in tension is accompanied by a high frequency burst of impulses from the stretched muscle spindle, called the 'initial burst' (Proske & Stuart, 1985). Morgan, Prochazka, & Proske (1984) discovered that repetitive movements or fusimotor stimulation caused the stable bridges to become detached.

Soon after, the bridges spontaneously re-attached at whatever length the muscle was being held. In this way, resting spindle discharge frequency can be manipulated by putting the muscle in a defined state. A muscle shortened from a length at which stable cross bridges have formed will tend to fall slack due to the stiffened intrafusal fibers. The result is a lower resting Ia afferent discharge frequency. This is known as 'extension conditioning'. Conversely, if a muscle is stretched from a length at which stable cross-bridges have formed the intrafusal fibers will remain taut and the resting rate of Ia afferent discharge will be higher. This type of conditioning has been termed 'flexion conditioning' (Proske & Gandevia, 2012; Wood, Gregory, & Proske, 1996).

The thixotropic state of a muscle has been found to have profound effects on position sense. Thixotropic-dependent errors in position sense are typically only present in the passive limb which strongly implicates the resting activity of muscle spindles as generating a signal of limb position (Proske & Gandevia, 2012). During bilateral matching, a passive muscle that is flexion conditioned, then moved to a slightly more extended position leads blindfolded subjects to perceive their limb as being more extended than it actually is, conversely, a muscle that is extension conditioned than moved into a slightly more flexed position leads subjects to perceive the limb as being more flexed (Allen et al., 2006; Lee D. Walsh, Smith, Gandevia, & Taylor, 2009). Ansem, Allen & Proske (2007) hypothesized that the muscle spindle is mainly a stretch receptor and this helps to explain conditioning dependent errors in perceived limb position. In a lengthened muscle, increased resting spindle discharge rate is perceived by the brain as a longer muscle and vice versa for a shortened muscle. They further investigated conditioning dependent errors by adding weight to the reference limb during matching trials. It was found that during load bearing the skeletomotor activity required to support the load was accompanied by fusimotor co-activation which led to a removal of slack in the intrafusal fibers in the shortened muscle such that position errors were drastically reduced. Ansems et al. found that a contraction of around 10% of MVC was enough to co-activate the gamma motor neurons in elbow muscles.

The effects of thixotropy on position sense strongly implicate the roll of the muscle spindle in providing the CNS with information regarding the length of the muscle. However, studies on the effects of muscle vibration support the roll of the muscle spindle as also being the prime mechanoreceptor for providing information to the CNS on the speed of limb movement, as well.

Vibration. Goodwin, McCloskey and Matthews (1972) discovered that vibration on the tendon of the biceps or triceps muscle caused subjects to systematically misjudge the angle of their elbow and place their limb in the position that it would have assumed had the vibrated muscle been stretched. This was discovered using a bilateral matching paradigm where the subjects were asked to match the perceived location of the vibrated arm (reference arm) with their other, non-vibrated arm (indicator arm). In 1988 Gregory, Morgan and Proske found that vibration of the cat soleus muscle resulted in similar activation of the primary afferents compared to contraction conditioning which strongly implicates the muscle spindle as being the primary sensor of kinesthesia. The recordings from single afferents confirmed that the alterations in discharge could be attributed to the primary and secondary endings of muscle spindles. McCloskey and Sittig, Denier and Gielen (1985) believed the perception of joint movement and displacement to be separate. Cordo, Gurfinkel, Brumagne & Flores-Vieira (2005) found conflicting evidence when, after approximately 16 seconds of continuous triceps tendon vibration, subjects no longer perceived their forearm to be moving and the perceived position of the joint also stopped changing, but they did perceive it to be displaced. This implies a certain amount of interdependence between movement and position senses.

Further details of the vibration illusion were provided by McCloskey (1973) who showed that the speed of the vibration illusion slowed in direct proportion to the load being supported by the vibrated muscle. When muscles produced around 50% of MVC or more, vibration no longer produced any movement illusion. Ansems, Allen and Proske (2006) confirmed McCloskey's observations when they found that loading the arm progressively removed conditioning-dependent position errors, presumably because of spindle co-activation through the fusimotor system. Another important observation from the study was that the absence of a vibration illusion with a loaded muscle suggests that position sense is not derived from a spindle alone; at least not the spindle signal evoked by vibration and may involve central origin.

Joint receptors, Golgi tendon organs and muscle spindles all contribute to JPS, but how exactly is the stream of afferent information coming from the individual mechanoreceptors used to determine the variables of interest (segment location and movement speed)? Afferent information from a single mechanoreceptor hardly provides useful information. Instead it is the combined contribution of afferent information derived from a population of mixed proprioceptors that is thought to be used by the CNS in the calculation of joint position sense. This has been termed 'population coding'.

Population Coding. While there is ample evidence to support the hypothesis of the muscle spindle being the primary receptor for kinesthesia and JPS (Proske & Gandevia, 2009; Uwe Proske, 2006), what is less clear is how the ensemble of proprioceptive information is used by the CNS to determine joint position and movement velocity. Georgopoulos, Caminiti, Kalaska and Massey (1983) studied the discharge characteristics of single neurons in the motor cortex of rhesus monkeys while the animals performed two-dimensional arm movements on a plane working surface. They found that the frequency of discharge for most of the cells (75%) varied in an orderly fashion with the direction of the movement and that the discharge was most intense with movements in a preferred direction. Perhaps the most important finding was that movements in a certain direction engaged neurons with overlapping directional tuning curves. The implication is that direction of movement is not promoted by cells uniquely related to a particular direction but is instead encoded by a population of cells that responds, as a group, to a specific direction (Georgopoulos, Caminiti, & Kalaska, 1984). This is what has been termed the "neuronal population vector model". Bergenheim, Ribot-Ciscar and Roll (2000) applied this model to a population of muscle spindle afferents in order to show that the parameters of multidirectional ankle joint movements were accurately encoded when all the proprioceptive information from all the muscles involved in the movement were taken into account. Not only did muscle spindles belonging to one particular muscle respond to a certain range of directions of stretching movements (termed the "muscle preferred sensory sector"), they were more sensitive to one particular direction called the "muscle preferred sensory direction". Interestingly, Bergenheim et al. found that the direction of the vibration illusion closely corresponded to each individual muscle's preferred sensory direction. In agreement with the above findings Ribot-Ciscar, Bergenheim, Albert and Roll (2003) showed that the net vector resulting from the population of muscle spindle afferents surrounding the ankle joint was a good predictor of the direction in which the target position was spatially located relative to the home position for two dimensional movements on a plane working surface (the home location was defined as the middle of the plane surface while target positions were located, at equal intervals, in a circular fashion around the home position). The previous observation was only the case when the patterns of activity of all the muscle populations were considered. More specifically, static joint position correlated closely with the hold rate (the average firing rate of muscle spindle primary endings during the portion of a hold period prior to the onset of movement) and the initial burst (the average rate of the interspike intervals occurring during the start of movement) (Cordo, Flores-Vieira, Verschueren, Inglis, & Gurfinkel, 2002). Ribot-Ciscar et al. also showed that a movement direction that caused a maximum decrease in the mean firing rate of the antagonist muscle group caused a maximum increase in the mean firing rate of the agonist muscle group. This observation is interesting since the direction of a slow movement could be specified on the basis of the spindle discharge rate while the velocity of a movement might be correlated with the difference between the spindle activity occurring in the agonist and antagonist muscles (Ribot-Ciscar & Roll, 1998). Importantly, mixed populations of primary and secondary muscle spindle afferents and Golgi tendon organ afferents distinguish between muscle stretches of different amplitudes better than populations consisting of a single type of afferent which implies that JPS acuity is more accurate when a diverse array of afferent information, coming from multiple mechanoreceptors, is used together (Bergenheim, Johansson, & Pedersen, 1996).

Passive vs. active matching. Early position sense experiments used passive tests such as threshold to detection of passive motion (TTDPM) and reproduction of passive positioning (RPP). While these tests have been illuminating for specific mechanisms, they have ignored a key role of position sense which is to provide information to the CNS about an active limb in a dynamic environment. Hung and Darling (2012) compared a unilateral unconstrained active repositioning task with passive matching tasks in individuals with and without shoulder instability. They found that subjects with instability exhibited significantly larger matching errors than those subjects with healthy shoulders during passive matching. During active repositioning tasks (abduction and rotation paradigms) there was no significant difference in matching errors between the unstable and healthy groups. Similarly, Erickson and Karduna (2012) showed that subjects matched more accurately with active placement of their limb compared to passive placement. One explanation for the increase in matching accuracy in active versus passive tests may be due to the enhanced muscle spindle sensitivity accompanying greater skeletal muscle activation (Suprak et al., 2006, 2007). Suprak et al. (2006) discovered that shoulder JPS improved with humeral elevation up to ninety degrees and it was proposed that a potential mechanism for increased JPS acuity may have come from the increased levels of muscle activation required to maintain the segment during increasing levels of elevation. This idea was supported when Suprak (2007) performed a similar experiment but this time added weights to the hand such that the repositioning angles were the same but the external load was changed. He found that repositioning errors decreased linearly as the external load increased up to 40% above unloaded shoulder torque. In both studies, repositioning at ninety degrees of humeral elevation showed the smallest errors.

In order to study the potential contribution from the capsuloligamentous structures Suprak (2011) had subjects actively match positions at varying degrees of horizontal abduction, but constant elevation, such that the torque due to gravity was constant in all positions. It was believed that, as the subjects moved closer to the end range of motion for horizontal abduction, the capsuloligamentous structures would become tighter and position errors would become less due to tighter approximation. No main effect was found for position on matching errors and it was concluded that shoulder joint position sense appeared to be enhanced as the external torque on the joint increased, regardless of the proximity to the end ROM.

It is apparent that muscle activation, and therefore muscle spindle co-activation play an important role in position sense and the information coming from spindles seems to override the information arising from the capsuloligamentous structures. However, there is conflicting evidence with regards to the torque hypothesis. Chapman, Suprak and Karduna (2009) conducted an experiment at the shoulder in which subjects' trunks were tilted backwards to decouple joint angle from joint torque. This allowed for a comparison of JPS at different joint angles (at the same resistive torque) and at different resistive torques (at the same joint angles). They hypothesized that JPS accuracy is primarily affected by changes in resistive torque rather than by changes in joint angle. When comparing the two tilts, they found that repositioning based on elevation angle demonstrated no significant difference, while matching based on torques did exhibit differences. Their results implicate elevation angle at the shoulder as playing a more important role in regulating JPS than joint torque. It is also possible that the increase in JPS acuity observed with active repositioning test where external resistance is increased could come from the larger motor command accompanying the larger external resistance. Whatever the case may be, central mechanisms cannot be overlooked.

Central command. The peripheral nervous system provides a large amount of information back to the CNS regarding the position of the segment, if static, and the position and velocity of the segment while dynamic. However, the CNS can provide information to itself regarding the position and velocity of a static or dynamic segment. The following topics will include the roll of signals of central command and effort and how they combine with peripheral signals to influence joint position sense.

While peripheral signals of proprioception are important for fine-tuning movement they are only one part of the whole system. For example, fusimotor co-activation has traditionally been thought to occur directly with muscle activity; however this may not be the case. Ribot-Ciscar, Hospod, Roll and Aimonetti (2008) found that selective attention to movement velocity gave rise to a significant increase in the dynamic and static responses of muscle afferents. In contrast, focusing attention on the final position reached made the muscle spindle feedback better discriminate positions and depressed its capacity to discriminate movement velocities. By setting the tension of intrafusal muscle fibers, the fusimotor system modifies the static and dynamic sensitivity of muscle spindle endings. This is significant because it implies that the central nervous system is able to selectively and differentially control the sensitivity of muscle spindles in humans.

An important aspect of proprioception is that not all the signals generated by movement reach consciousness. What we perceive is only the exafferent component, or the component that results from occurrences in the environment rather than the inputs that arise from our own movements (reafference) (Holst & Mittelstaedt, 1950). It is well known that muscle spindles are inherently noisy, meaning that they produce many afferent impulses that obscure or reduce the clarity of the kinesthetic signal. Which is why some researchers argue that the role for the evolution of independently controllable fusimotor neurons is to optimize the resolution of the received information in the face of noise in the neural signal itself (Scott & Loeb, 1994). It has been known for a long time that movements can induce sensory inputs that are indistinguishable from the input that is caused by external agents. Animals circumvent this problem by routing copies of movement commands to sensory structures. These are referred to as corollary discharge (CD) signals or efference copies (EC) (Crapse & Sommer, 2008a). CD is essentially a mechanisms that allows animals to ignore sensations resulting from their own actions, and tag them as ‘self’ (Ford, Roach, & Mathalon, 2010). CD circuits have substantial support in primates (Crapse & Sommer, 2008b; Sommer & Wurtz, 2006) but the study of CD in humans is more difficult due to the invasive nature of the techniques. However, recently non-invasive neurophysiological techniques have been used to assess the operation of CD in humans (Ford et al., 2010). Moreover, proprioception is phylogenetically old and central to the daily survival of animals which suggests significant coevolution (Scott & Loeb, 1994).

In order to remove noise, it is believed that the CNS filters sensory data, one example being the reduction in tactile sensitivity observed during self-touch compared to being touched by someone else (Blakemore, Frith, & Wolpert, 1999). In everyday activities, such sensory suppression would allow us to focus attention on external stimuli and be less distracted by the sensations arising from our own movements (Proske & Gandevia, 2012). A study by Voss, Ingram, Haggard and Wolpert (2005) used pulses of transcranial magnetic stimulation (TMS) over the primary motor cortex of human subjects to delay planned finger movements at the motor output stage. Sensory suppression of cutaneous stimuli was observed at the intended time of movement, despite this being substantially prior to the actual onset of movement. The authors concluded that a significant component of sensory suppression arises from the central signals related to the preparation of motor commands. More specifically, a model of sensory filtering has been suggested where self-generated sensations are predicted based on an efference copy of the motor command. In this way, motor commands may be used to estimate the current and future positions of a limb as well as the sensory consequences of planned movements, a mechanism known as forward modeling (Coslett, Buxbaum, & Schwoebel, 2008). By subtracting this prediction from the incoming sensory stream (proprioceptive), the self-generated (reafferent) component can be removed (Bays & Wolpert, 2006). In essence, actual sensory feedback is compared with predicted sensory feedback in a difference calculator; and the inequality between the two is what is perceived.

Blakemore, Wolpert ad Frith (1998) used functional magnetic resonance imaging (fMRI) to examine the neural responses when subjects experienced a tactile stimulus (tickling) that was either self-produced or externally produced. They found that more activity was found in the somatosensory cortex when the stimulus was externally produced. They also observed greater cerebellum activity with movements that did not result in a tactile stimulus where cerebellar activity was decreased in movements that generated a tactile stimulus. This suggests that the cerebellum is involved in predicting the specific sensory consequences of movements. In the self-touch example given above, Blakemore, Frith & Wolpert (1999) believed that the extent of attenuation of self-produced tactile stimulation (i.e. tickling) was proportional to the error between the sensory feedback predicted by an internal forward model of the motor system and the actual sensory feedback produced by the movement. To simplify, when the sensation no longer corresponds to the motor command, the predicted image of the afferent signal (in this case a tickle stimulus) does not fully cancel the distorted reafference (Cullen, 2004). Recently a model has been proposed for the attenuation of self-generated movements (Bays & Wolpert, 2006).

Evidence for a central difference calculator was recently supported by Izumizaki, Tsuge, Akai, Proske and Homma (2010) who discovered that a difference signal is calculated from input coming from both arms. They studied the matching position illusion from vibration of the reference arm while the indicator arm was held stationary, moved into extension and moved into flexion. They discovered that the speed of the illusion of elbow extension evoked by vibration of the reference arm could be altered by movement of the indicator arm. Movement of the indicator arm into extension decreased the perceived motion of the reference arm into extension. Movement of the indicator arm into flexion increased the perceived motion of the reference arm into extension. The authors hypothesized that the combined processing of inputs from both arms could serve as part of a motor control strategy for use of the two hands together as a single instrument in certain skilled tasks.

Motor commands are used in the parietal cortex to generate expected sensory outputs (McGonigle et al., 2002) and reach the pre-motor cortex to construct movement corrections when errors arise (Wolpert, Ghahramani, & Jordan, 1995). In order to understand more about motor commands Melzack and Bromage (1973) induced an experimental phantom limb by producing an acute block of sensory and motor nerves to the limb of interest. Along these lines Inui, Walsh, Taylor and Gandevia (2011) studied the effects of ischemic sensory and motor block of the arm on the perceived posture of the hand as the block developed. They found that subjects who started with their hand flexed indicated their limb as being more extended at the wrist and fingers after the block. Subjects who started with their hands and fingers extended perceived their limbs to be more flexed when the block had fully set in. It was proposed that, as the input from sensory receptors 'fades' during the anesthesia, the subject perceives the hand to move away from its initial maintained position. As conduction block progressively develops, the reduction in firing rate for the population of 'flexion encoded' receptors will be greater than for extension encoded receptors. Such a differential response would lead to the perception of the hand moving away from its initial position.

While It is well known that alterations to afferent information impact joint perception, what is less understood is how motor commands effect sensory perception when there is a complete block of both sensory and motor neurons. Walsh, Gandevia and Taylor (2010) aimed to determine if subjects could perceive continuous movements of a paralyzed and anesthetized wrist when they made voluntary efforts into flexion and extension. Complete sensory and motor nerve block was confirmed by electromyography (EMG). Greater efforts resulted in greater illusory speeds while longer duration efforts and greater illusory speeds resulted in larger perceived displacement of the phantom limb. It was concluded that, in the absence of sensory feedback, motor command signals related to the wrist are the dominant contributor to the perception of movement. Another, similar study by Gandevia, Smith, Crawford, Proske and Taylor (2006) made similar conclusions; they also found that greater efforts resulted in greater movement and displacement illusions. They hypothesized that gradation of the size of the illusion with effort might indicate signals of motor command as being more important for position sense during loading rather than unloading contractions.

Sense of effort. Almost everyone has experienced the altered limb sensations accompanying intense exercise; often-times people feel unstable, shaky or weak. Fatigue has been shown to decrease proprioceptive sense in reproduction of passive positioning and threshold-to-detection-of-passive-motion tasks at the shoulder (Carpenter, Blasier, & Pellizzon, 1998). More importantly active matching after muscle fatigue has led to the hypothesis that a central effort signal contributes to position sense (Fortier, Basset, Billaut, Behm, & Teasdale, 2010; Fortier & Basset, 2012; L D Walsh, Hesse, Morgan, & Proske, 2004; L. D. Walsh, 2005) and has been termed the “sense of effort”. The simplest explanation comes from the observation that subjects match the effort required to achieve a given force, not the forces themselves (Winter et al., 2005). Others have made the observation that, during bilateral matching tasks, the exercised indicator limb adopts a systematically more flexed posture in matching the position of the reference limb because reduced voluntary torque after exercise is accompanied by a greater effort required to support the arms, leading to larger matching errors (Walsh, 2005) . However, effort is only able to provide positional information for unsupported matching tasks where gravity plays a role. In gravity neutral tasks, like counterweighted (Gooey, Bradfield, Talbot, Morgan, & Proske, 2000) or horizontal matching (Ansems, Allen, & Proske, 2006), a change in the effort-force relationship after exercise leaves matching accuracy unaffected since the external torque acting on the segment of interest remains unchanged.

The idea that the sense of effort accompanying support of a load provides positional information in any simple way is an oversimplification. Allen, Ansems & Proske (2007) argued that when muscles are active, position sense involves operation of a forward internal model and that loading the arm produces predictable changes in motor command outputs and afferent feedback whereas changes after exercise are unpredictable and this difference leads to exercise-dependent errors during bilateral matching tasks. The sense of effort does not follow any simple mechanism. Allen et al. (2007) also hypothesized that, in a comparison between the expected afferent feedback, recalled from previous experiences in a non-fatigued muscle, the feedback from the fatigued muscle is interpreted as the muscle being longer, that is, a more extended forearm after exercise of elbow flexors and a more flexed knee after exercise of knee extensors. In another study, Allen, Leung and Proske (2010) found that this was not the case. They observed errors in the same direction from exercising each of the antagonists, both at the elbow and knee. Fatigue of the elbow extensors produced errors in the direction of elbow extension while fatigue of leg flexors produced errors in the direction of flexion. Previous attempts to provide an explanation for the effects of exercise induced fatigue on position sense have been constructed around peripheral mechanisms. However, animal experiments have shown that vigorous exercise does not interrupt the normal response properties of muscle spindles (Gregory, Morgan, & Proske, 2004). Given this information, Allen, Leung and Proske (2010) concluded that, while the factors that trigger the effects of exercise on position sense may have their origin in the periphery, they exert their influence on position matching performance centrally, within the brain.

More recently it has been argued that, if ordinary muscle fibers are going to be damaged by eccentric exercise, the intrafusal fibers of muscle spindles must, in turn, be altered and that such damage to intrafusal fibers could help to explain the change in JPS acuity observed following fatigue. However, all muscle contraction types have been shown to induce position matching errors (Fortier et al., 2010). The observation that both eccentric and concentric muscle contractions produce position matching errors implies that muscle damage associated with eccentric exercise is not a contributing factor to impaired JPS and kinesthesia (Fortier & Basset, 2012). Along these lines it has recently been shown that eccentric contractions, which induce muscle damage, do not appear to have any effect on spindles (Gregory et al., 2004). This observation helps to reinforce the idea that the effort required maintaining the position of a limb against the force of gravity provides an important positional cue. As stated earlier, if subjects match efforts to align their arms they will place the exercised arm more nearly vertical where less force is required to support it (assuming the segment isn't already vertical), leading to position matching errors. Adoption of a more vertical position is advantageous to a fatigued limb since it requires less effort, for two reasons. First, the torque on the segment due to gravity is less. Second, a more vertical position is closer to the elbow flexors' optimum length for active tension (Fortier & Basset, 2012).

Summary

The body of literature supports the role of both the peripheral and central nervous systems in the computation and fine tuning of joint position sense. Afferent information coming from joint, Golgi, and muscle mechanoreceptors are crucial for the CNS to be able to properly determine the position of a body segment in three dimensional space, and while information coming from entire populations of mechanoreceptors are crucial for accurate calculations of JPS, the muscle spindle is the primary receptor for kinesthesia as supported by the muscle thixotropy and vibration studies.

More recently, active unconstrained repositioning paradigms have been instituted to study the effects of JPS under the effects of gravity without limiting active ROM. There are many differences in matching errors observed between active unconstrained, active constrained, and passive constrained matching/repositioning paradigms. In general, matching appears to be more accurate under active unconstrained conditions, presumably because of the level of muscle activation required to move and maintain a limb against gravity. However, there is support for elevation angle at the shoulder playing a more important role in modulating joint position sense than joint toque, though central mechanisms cannot be ruled out.

Larger motor commands and a larger sense of effort also accompany active unconstrained matching during progressive shoulder elevation up to ninety degrees. Importantly, the CNS uses motor commands in the preparation of movements. These motor commands have been shown to cause illusory sensory movements and positions in people with experimental phantom limbs. In this case it has been hypothesized that a forward model is used by the brain to compare predicted proprioceptive information with real–time afferent information in a central difference calculator.

The information is compared and the difference between the predicted and real information is what we perceive. In the case of the phantom limb, there is no afferent information making it back to the CNS due to sensory blockade so what is perceived comes purely from the motor command.

The CNS is able to actively adjust and tune the sensitivity of both static and dynamic endings of muscle spindles so that it can better discriminate between segment position and movement velocity. But this creates a serious problem. Activation of the fusimotor system causes noise in the neural signal that, in theory, should be perceived as an increase in segment motion or displacement, but this is not the case.   Motor commands signals are thought to be heavily involved in discriminating between reafferent and exafferent stimuli. Copies of motor commands, called efference copies, are routed to processing regions in the brain to take the reafferent signal into account so that they are not perceived. This is thought to be the driving mechanisms behind why tickling yourself results in no sensitivity yet being tickled by someone else can result in extreme sensitivity.

Finally, the sense of effort, while not fully understood, provides a positional cue based on voluntary effort. This cue provides predictable feedback to a forward model that allows for greater acuity of JPS when combined with afferent information. However, fatigue due to exercise is thought to alter the predictability of afferent information such that calculations in the forward model become inaccurate, leading to position matching errors.

Chapter III

Methods and Procedures

Introduction

In order to determine which contributes more to JPS accuracy in an unconstrained repositioning task; resistive torque (as modulated by body orientation) or shoulder joint angle, a study was conducted to measure the effects of these two variables on unconstrained active position matching errors in a healthy college aged population.

Description of Study Population

Thirty-five subjects (27 female, 8 male) with a mean age of 23 ± 3 years (Mean ± SEM), a mean height of 171 ± 9 cm, and a mean body mass of 70.0 ± 14.6 kg participated in the study. Subjects were excluded from the study if they had a history of shoulder pathology requiring surgery or rehabilitation, limited ROM in scapular plane arm elevation, previous diagnosis of shoulder instability, or other pathology that might alter the neuromuscular control of the shoulder. In addition, no individuals scoring a 4 or higher on the Beighton Hypermobility index were included (6 or greater indicates generalized joint hypermobility).

Design of the Study

A repeated measures observational study was employed to examine the effects of muscle activation, modified by body orientation, and humeral elevation angle on shoulder JPS. Subjects performed unilateral unconstrained shoulder repositioning tasks at three angles relative to the thorax (70°, 90° and 110°) while sitting in an upright position and lying in a supine position.

Data Collection Procedures

All testing was completed in a single session and performed on the dominant upper limb. Subjects performed a standardized warm-up procedure that has been described previously (Suprak et al. 2006). Following the warm-up procedure subjects removed their shirts (females wore sports bras) and all neck and arm jewelry in order to restrict tactile cues during testing. Subjects were seated on a custom made bench with back and head support so that there would be equivalent and minimal tactile stimulus as well as equivalent positions of all body segment in the seated and supine positions (figure 1).

Instrumentation. Kinematic data were collected using the Polhemus Fastrak 3Space magnetic tracking system (Colchester, VT), consisting of a transmitter, three receivers and a digitizer. To track the movement of the humerus with respect to the thorax during testing, one receiver was taped on the sternum, approximately 1.5 cm inferior to the jugular notch (Borstad & Ludewig, 2002), and one on the humerus, just above the lateral epicondyle, secured with a custom-molded Orthoplast cuff and Velcro strap. In addition, one receiver was fastened to the acromion process for digitization purposes, but was removed prior to testing (Karduna et al., 2001). Following attachment of the receivers, with the subject seated, various bony landmarks were digitized on the thorax and humerus in order to establish the anatomical coordinate systems, in accordance with the standard endorsed by the International Society of Biomechanics (Wu et al., 2005). The body segments and corresponding digitization points were as follows, thorax: C7, T8, jugular notch, and xiphoid process; humerus: medial epicondyle, lateral epicondyle, and humeral head. The center of the humeral head was calculated using a least squares algorithm and was defined as the point that moved the least during several small arcs of motion (Harryman, Sidles, Harris, & Matsen, 1992).

Measurement techniques and testing procedures. Subjects were asked to sit on the chair facing forward with the torso erect and flat against the back. While maintaining this trunk and head position subjects elevated the humerus to 70°, 90° and 110° in the sagittal plane with respect to the thorax, as confirmed with a real-time display of plane and elevation angles via custom-written LabView software. After subjects performed matching tasks for the three elevation angles in the upright position the bench was adjusted such that the subjects were moved 90° back from a sitting position to a supine position. Subjects again elevated the humerus to 70°, 90° and 110° in the sagittal plane with respect to the thorax.

The testing protocol was thoroughly explained to the subjects while watching the visual output, first on the computer, then through the head-mounted display. A gray scale with a black square in the center was presented to the subject, via custom written LabView software. The black square represents the target position for a given trial. On the four sides of the screen, rectangular boxes appeared in order to prompt subjects as to which direction to move their arm in order to arrive at the target position (figure 2).

All trials began with the arm at the side. Subjects were instructed to move their arms in the direction of the rectangular boxes. When the actual shoulder position was within five degrees of the target position in both plane and elevation angles, all of the boxes disappeared and a red dot appeared on the screen, representing the instantaneous shoulder position (figure 2). Subjects continued to position the arm until the red dot on the screen was inside the black square, indicating that the shoulder was in the target position. The borders of the square represented a boundary of 1° in either direction from the target position, with respect to the plane and elevation angles. Once the shoulder was in the target position for one second, an audible "beep" was heard and the screen turned black and remained that way for the rest of the trial. Subjects were instructed to maintain their shoulder in the target position for a five second period, during which time they were to concentrate only on the position of the shoulder. After the subjects had maintained the target position for five seconds, a computer generated voice instructed subjects to "relax", at which time the subject lowered the arm down to the side.

Three seconds after the arm was returned to the side, another computer generated voice instructed subjects to "return". Subjects then attempted to replicate the presented target position in both plane and elevation angles. When subjects perceived that the shoulder was at the target position, they used the contralateral hand to push a trigger button interfaced with the computer in order to record the reproduced position. Subjects were instructed to maintain the shoulder in the reproduced position for one second after pushing the trigger button, at which time an audible "beep" sounded and the trial ended.

During all trials, subjects were instructed to keep their backs straight and face forward while in the seated position. Verbal corrections were offered if posture changed at any time during testing. Therefore, although the visual display provided cues to aid subjects in reaching the target position for each trial, the target position was always seen by the subjects as being straight ahead in their visual field. The visual display would, therefore, not have provided useful information for subjects in determining the shoulder position. Prior to the start of testing, subjects performed several practice trials (at least three) at a target position consisting of a plane 45° anterior to the frontal plane and 60° of elevation. The practice trials were repeated until subjects felt comfortable and confident in performing the task.

In order to address the effects of shoulder elevation in the vertical plane on unconstrained JPS in both the seated and supine positions three angles were selected in order to vary the amount of external torque. These positions included the angles 70°, 90° and 110° of elevation, all in a plane 80 degrees anterior the frontal plane. Within each trial sequence, each of these three positions were tested three times, for a total of nine trials. These trials were automated by the software, and separated by a 15-s rest interval. The target positions were presented in a randomized order, according to a balanced Latin square design (Portney & Watkins, 2000). Starting condition (supine or upright) was randomized by a coin toss (heads for upright and tails for supine). Subjects completed two sequences of these nine trials (for a total of 18 trials), separated by five minutes.

In order to determine muscular activation of the shoulder a wireless desktop EMG system was used (Naraxon, Scottsdale, AZ). Electrodes were placed on the anterior and posterior deltoid muscles of the subjects dominate arm. EMG analysis was performed on the first 5 male and first 5 female subjects, for a total of 10 subjects. The EMG system was synced with the Polhemus magnetic tracking system via custom Labview software. Muscle activity was recoded at all three of the elevation angles in both the supine and upright conditions. Subjects used visual input from the custom Labview program, similar to the repositioning tasks except once they were at the proper elevation angle vision was not occluded. Subjects were asked to keep their arm steady in the box for a total of five seconds. After collecting data at the three elevation angles for each condition subjects performed a maximal voluntary isometric contraction (MVIC) for both the anterior and posterior deltoid muscles in order to normalize their data. For the anterior deltoid subjects flexed their arm 90 degrees in the sagittal plane, forearm flexed 90 degrees. Subjects pushed up into the hands of the tester for five seconds, as hard as they could. For the posterior deltoid MVIC subjects had their arm abducted 90 degrees in the frontal plane, forearm flexed 90 degrees. Subjects pushed back into the side of the tester as hard as they could for five seconds. In order to eliminate the effects of fatigue and learning on the repositioning tasks all instrumentation and muscle testing occurred after the repositioning trials were complete.

Statistical Analysis

Kinematic data were converted into humeral plane and elevation angles using transformation matrices between the coordinate systems of the thorax and humerus. Three dimensional vectors were calculated, using the plane and elevation angles defined by the lines running from the center of the humeral head through the midpoint between the medial and lateral epicondyles at the presented and reproduced angles. The angle between the presented and reproduced position vectors was calculated for each trial and taken to represent the absolute magnitude of the repositioning error (AE). The repositioning errors at each elevation angle were averaged over the three trials in each condition and the mean error was used for data analysis. Variable error (VE) was calculated to determine the consistency of subject performance using the following method:

$$\text{VE} = \sqrt{\frac{\sum (x_i - X)^2}{n}}$$

Where X_i is the AE for an individual trial and X is the AE averaged over the three trial sequence.

Statistical analyses were performed using SPSS, version 21 (SPSS, Chicago, IL). To determine the effects of body orientation (upright versus supine) and shoulder elevation angle (70 vs. 90 vs. 110 deg) on anterior and posterior deltoid muscle activity as well as absolute and variable repositioning error scores, a two-way, repeated measures ANOVA was conducted with two within-subject factors (body orientation and target elevation angles). Due to the nature of the assigned target angles, three target positions for each orientation were matched so as to require the same relative humeral elevation angle with respect to the thorax. For both analyses, if there was a significant effect of the orientation and a significant interaction between the two factors, follow-up paired t-tests were run with a significant interaction. The alpha level was set at 0.05. However, to account for multiple comparisons, a Bonferroni correction was utilized.

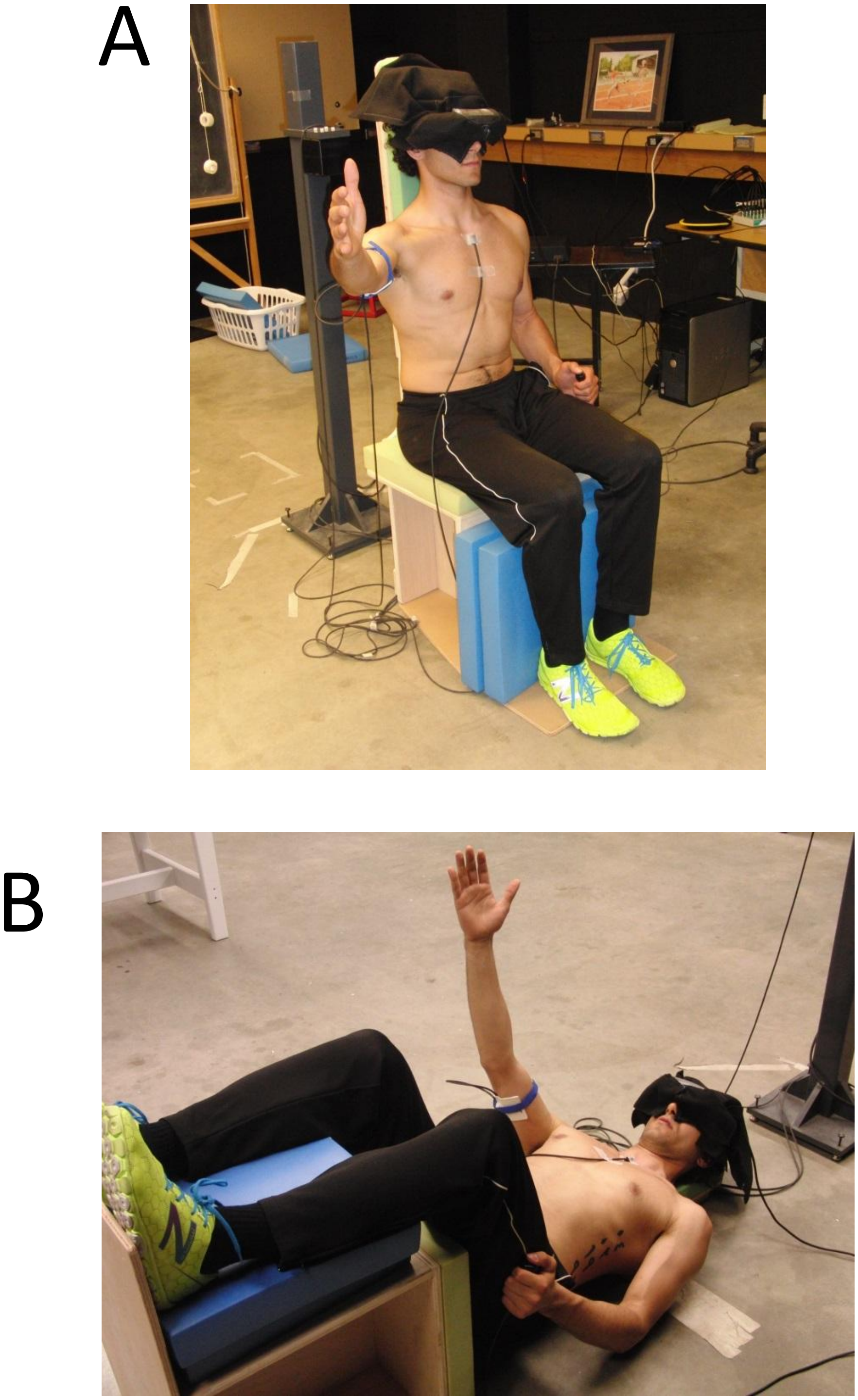

Figure 1. Experimental chair and set-up showing upright orientation (A) and supine orientation (B).

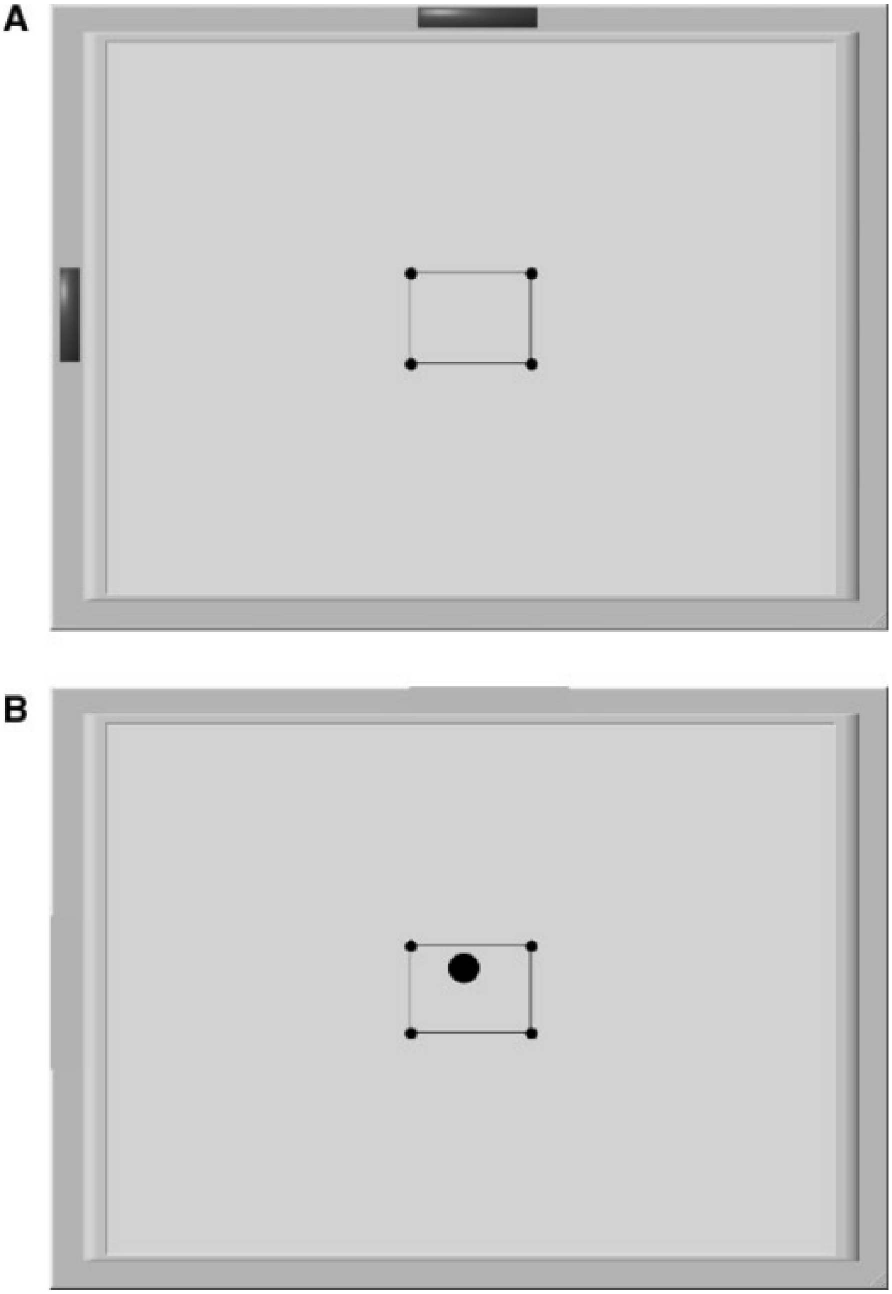

Figure 2. Computer output seen through the head-mounted display (A) guiding the subject to target position and (B) with the shoulder in the target position.

Chapter IV

Results and Discussion

Introduction

This study tested the hypothesis that shoulder JPS would be determined from joint angle and less from muscle activity and resistive torque during an unconstrained repositioning task. Kinematics were measured with a magnetic tracking device while muscle activation was measured with surface electromyography. The joint position sense task consisted of subjects moving their arms to a predetermined position in space with the help of visual feedback from a head mounted display interfaced with the magnetic tracking device. Subjects were then asked to reproduce the presented shoulder position in the absence of visual feedback. The protocol was performed under two body orientations: upright and supine (back 90 degrees from vertical).

Subject Characteristics

Thirty-five subjects with a mean age of 23 ± 3 years (Mean ± SEM), a mean height of 171 ± 9 cm, and a mean body mass of 70.0 ± 14.6 kg participated in the study (table 1). Subjects with a history of shoulder pathology requiring surgery or physical therapy, limited ROM in scapular plane arm elevation, previous diagnosis of shoulder instability, or other pathology that might alter the neuromuscular control of the shoulder were excluded. In addition, three subjects who scored positive for hypermobility according to the Beighton scale were excluded.

Table 1.

Subject Characteristics

	Mean	±SEM
Age (years)	23	3.89
Weight (kg)	70	11.8
Height (cm)	171	29

Results

The 2-way repeated measures ANOVA revealed a significant interaction between body orientation (upright vs. supine) and humeral elevation angle on vector error magnitude ($F[2, 68] = 9.90, p < 0.001, \eta^2 = 0.226$). Simple effects analyses revealed that vector error magnitude was significantly greater in supine compared to upright at 90 degrees ($t(34) = 2.51, p = .017$) and 110 degrees ($t(34) = 8.46, p < 0.001$), but not at 70 degrees ($t(34) = 0.12, p = 0.91$) (Figure 3). The ANOVA for variable error revealed no significant interaction between orientation and elevation ($F[2, 68] = 1.16, p = 0.32, \eta^2 = 0.03$) and no main effect of elevation ($F[2, 68] = 1.71, p = 0.19, \eta^2 = 0.05$). However, variable error was larger in supine (2.31° ± 0.12) than upright (1.73° ± 0.09) ($F[1, 34] = 21.48, p < 0.001, \eta^2 = 0.387$) (Figure 4). Mauchley's test indicated sphericity for both vector and variable errors. 10 subjects were used for EMG data (5 men and 5 women). The ANOVA for anterior deltoid muscle activity revealed a significant interaction between body orientation and humeral elevation angle ($F[2, 18] = 11.65, p = 0.001, \eta^2 = 0.56$). Simple effect analyses revealed that anterior deltoid muscle activity was significantly greater in upright at 70 degrees ($t(9) = 2.76, p = 0.022$), 90 degrees ($t(9) = 4.57, p = 0.001$) and 110 degrees ($t(9) = 4.76, p = 0.001$) when compared to the same elevation angles in the supine orientation (Figure 5). The

ANOVA for posterior deltoid muscle activity revealed no significant interaction between orientation and elevation angle ($F[2, 18] = 1.55$, $p = 0.24$, $\eta^2 = 0.15$). However, there was a main effect of elevation angle on posterior deltoid muscle activity ($F[2, 18] = 3.87$, $p = 0.04$, $\eta^2 = 0.30$) (Figure 6). Simple effects analysis showed that there was less activation of the posterior deltoid at 70 degrees compared to 110 degrees ($t(9) = 0.868$, $p = 0.014$), and no difference between 90 degrees and 70 degrees ($t(9) = 0.504$, $p = 0.469$) or for 90 and 110 degrees ($t(9) = 0.364$, $p = 1.00$).

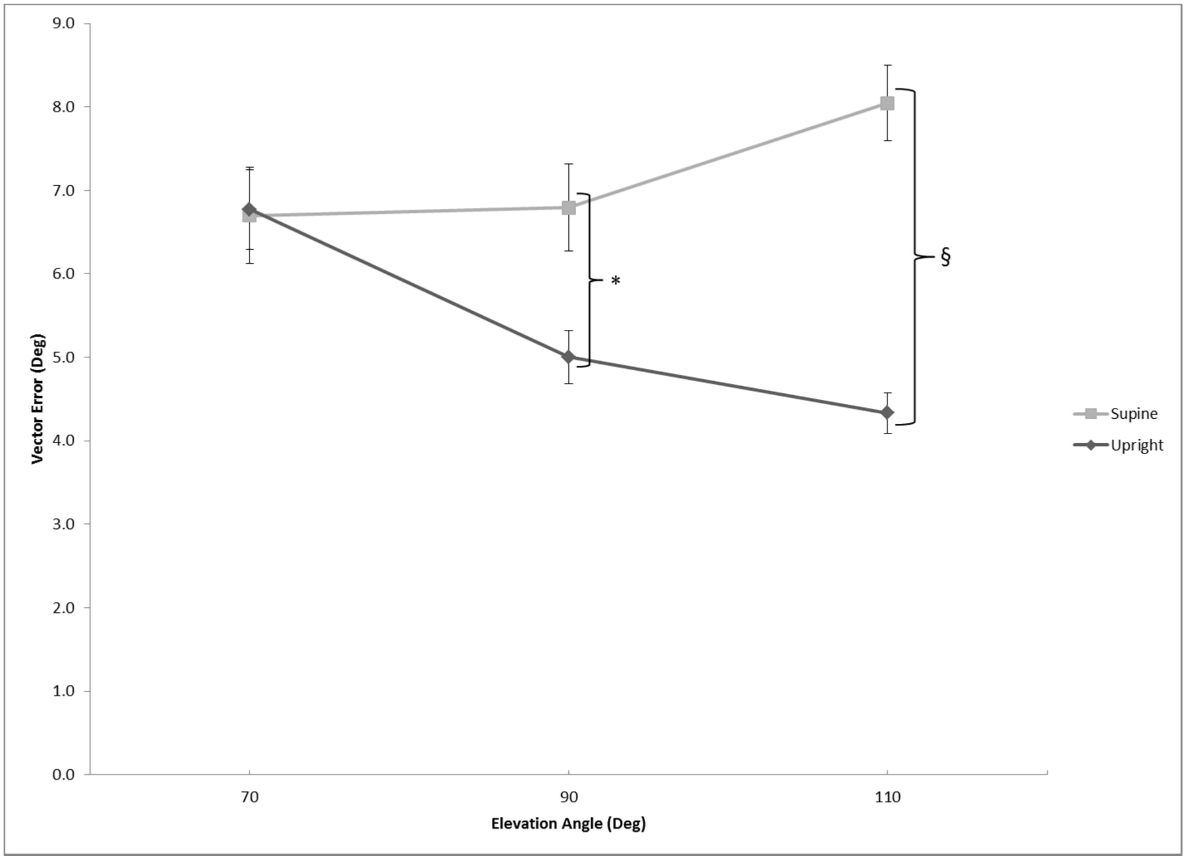

Figure 3. A graphical comparison of vector errors across two different body orientations and three different humeral elevation angles. * Indicates that the repositioning error is statistically higher at 90 degrees of humeral elevation in the supine condition when compared to the upright

one ($p = 0.017$). § Indicates that the repositioning error is statistically higher at 110 degrees of humeral elevation in the supine condition when compared to the upright one ($p < 0.001$).

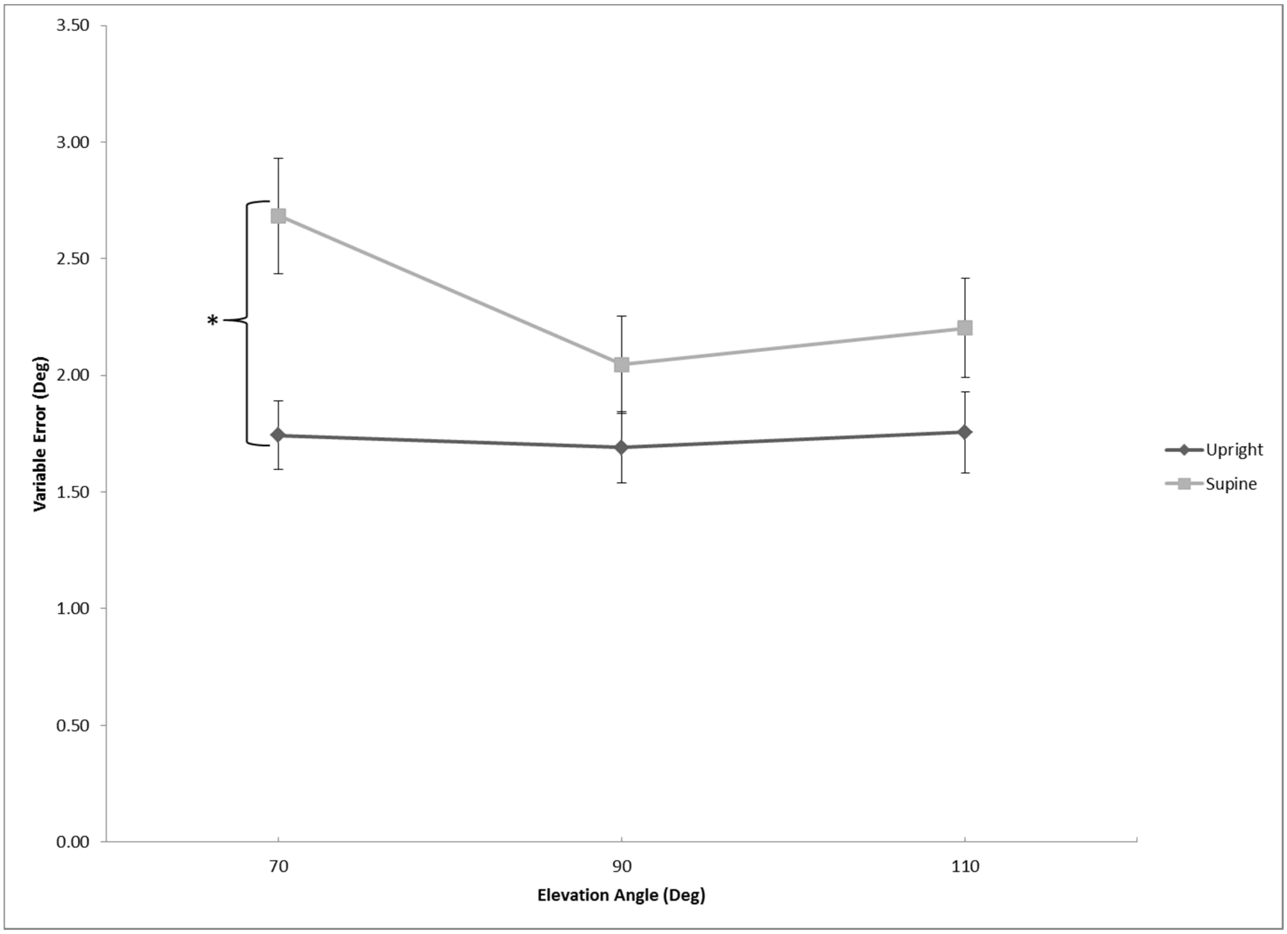

Figure 4. A graphical comparison of variable error across two different body orientations and three different humeral elevation angles. * Indicates a significant difference in variable error between the upright and supine conditions ($p < 0.001$).

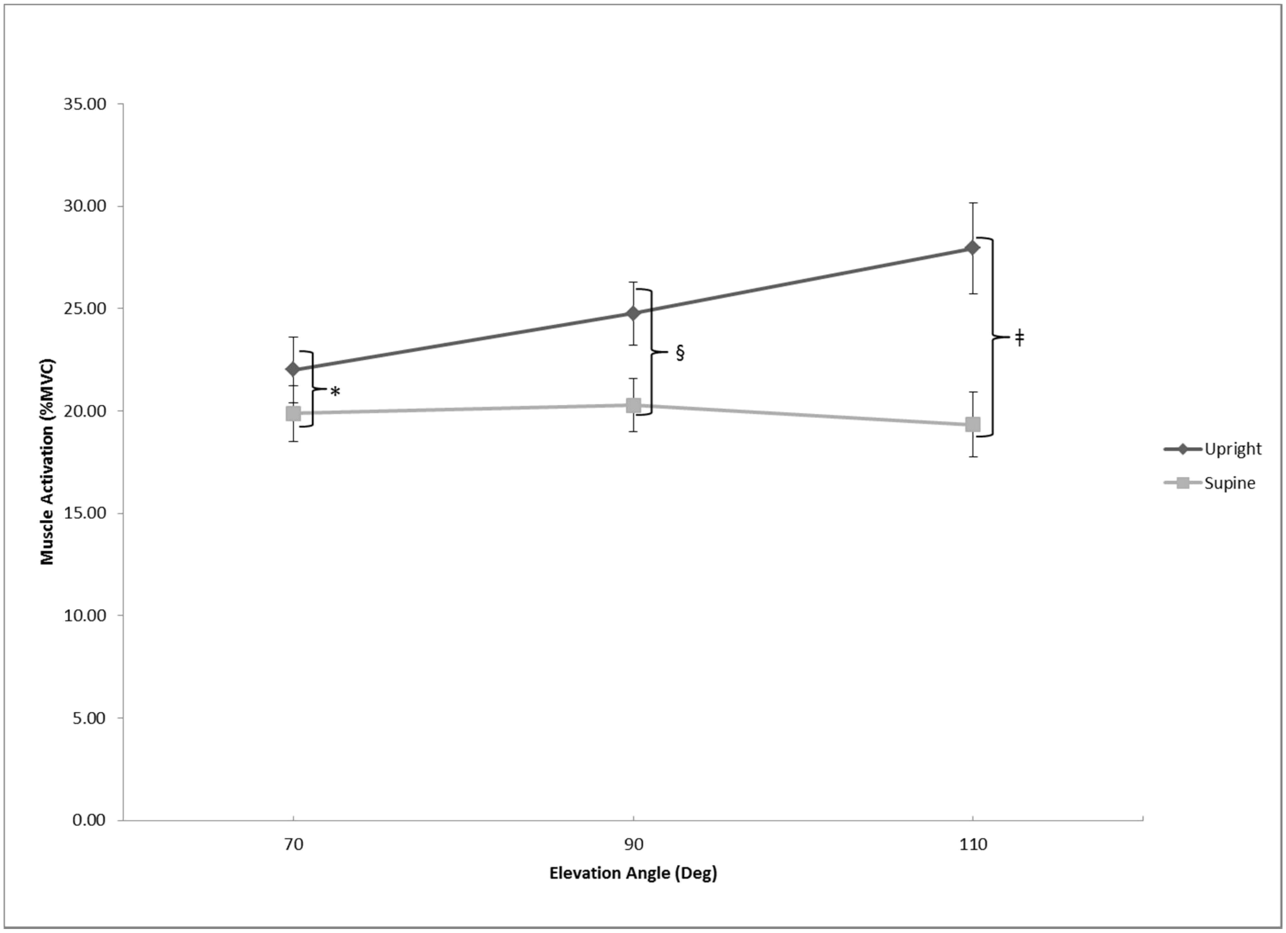

Figure 5. A graphical comparison of anterior deltoid muscle activation across two different body orientations and three different humeral elevation angles. * Indicates a significant difference in muscle activation between the upright and supine positions at 70 degrees of humeral elevation (*p* = 0.022). § Indicates a significant difference in muscle activation between the upright and supine positions at 90 degrees of humeral elevation (*p* = 0.001). ǂ Indicates a significant difference in muscle activation between the upright and supine positions at 110 degrees of humeral elevation (*p* = 0.001).

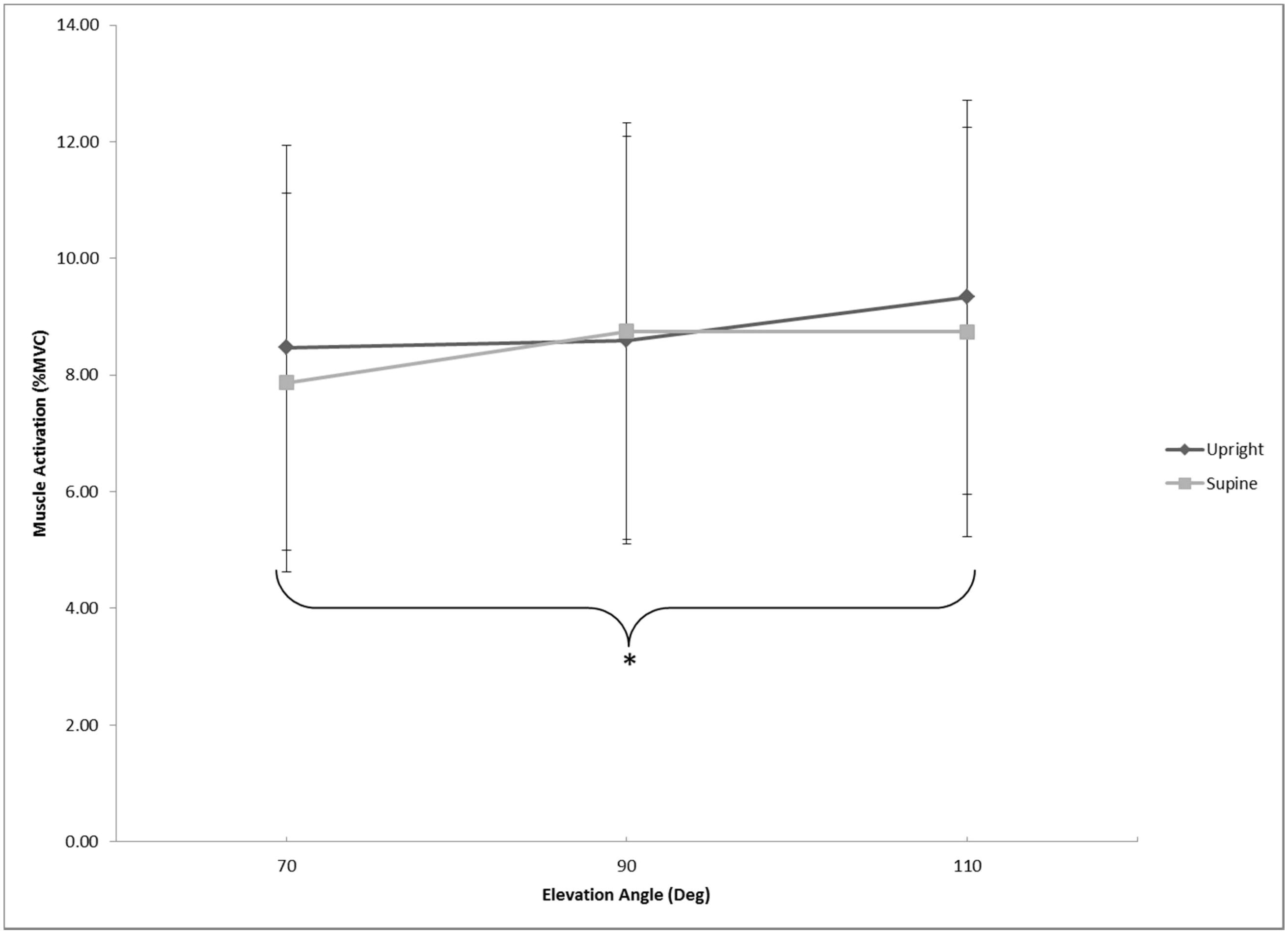

Figure 6. A graphical comparison of posterior deltoid muscle activation across two different body orientations and three different humeral elevation angles. * Indicates a significant difference in muscle activation of the posterior deltoid with progressive humeral elevation, regardless of the position ($p = 0.04$).

Discussion

The purpose of the present study was to examine the effects of body orientation and shoulder elevation angle on repositioning errors in an unconstrained joint position sense test. Based on previous research utilizing similar protocols (Chapman, Suprak, & Karduna, 2009; Suprak et al., 2006), and based on the idea that elevation angle (and thus, external torque and muscle activation levels) increase with shoulder elevation in the vertical plane, a chair was utilized that would allow for the comparison of shoulder repositioning errors at the same elevation angles but at different absolute body orientations. By having subjects attempt to reposition their dominant arm in both an upright and supine orientation we altered their alignment in the gravitational field, which allowed us to better determine if the increase in JPS accuracy previously noted with increasing humeral elevation angles (Suprak et al., 2006, 2007) was due to changing joint angles or external gravitational torque. Much like Chapman et al. (2009) we proposed that joint angle, and not joint torque would be primarily responsible for the increase in JPS accuracy. However, unlike Chapman (2009) who tilted subjects back 45 degrees from vertical, our subjects were reclined 90 degrees from vertical in the supine orientation. This way, matching at 90 degrees of humeral elevation would have the greatest torque due to gravity in the upright orientation while comprising the lowest torque in the supine orientation (due to the humerus being approximately parallel with the gravitational field). In this way joint angle and torque could be uncoupled. This is important because JPS accuracy has been observed to be the greatest at 90 degrees of elevation in unconstrained repositioning tasks (King & Karduna, 2014; Suprak et al., 2006). If JPS is determined more from joint angle and less from joint torque, then matching accuracy should be the most accurate at 90 degrees of humeral elevation regardless of the orientation of the body in the gravitational field. For this reason we hypothesized that JPS accuracy would be the greatest at 90 degrees of elevation in both the supine and upright conditions and that joint angle, and not joint torque would be primarily responsible for the increase in JPS accuracy observed with humeral elevation up to 90 degrees.

We found that our subjects did not match with a similar accuracy at 90 degrees of elevation across the two orientations. This finding is in contrast to Chapman (2009) who found a significant difference when matching accuracy was compared on the basis of joint torque but not on the basis of joint angle. Our results in the upright condition agreed with the literature in that matching accuracy increased with progressive humeral elevation (King & Karduna, 2014; Suprak et al., 2006). However, while it was not significant, there was a trend for increased accuracy at 110 degrees compared to 90 degrees. Matching accuracy did not show a significant increase with elevation in the supine position. On average, vector error was about 2 degrees greater in supine than upright, which is similar to the errors reported by Chapman et al. (2009).

In order to determine if muscle activity was, in fact, greater with the different body positions and elevation angles, we instrumented both the anterior and posterior deltoid muscles of a subset of subjects' dominate arms with electrodes for EMG analysis. Anterior deltoid activity was greater at all angles in the upright condition compared to the supine and increased with humeral elevation. Posterior deltoid activity did not change significantly with the body orientations or humeral elevation angles except for at 110 degrees of elevation when compared to 70 degrees, but only in the upright orientation. The increase in repositioning accuracy and anterior deltoid muscle activity observed with progressive elevation of the arm in the upright condition, and the noted decrease in both anterior and posterior deltoid muscle activity observed in the supine position supports the torque hypothesis, which states that the greater the resistive torque acting on a joint, the greater the matching accuracy of the subject.

The 90 degree condition is important with regards to both orientations and was specifically chosen to help determine if JPS was being computed more from joint torque or elevation angle. We found that muscle activity, while being larger in the upright condition, was still not at its highest at 90 degrees. The 110 degree elevation angle showed the greatest amount of muscle activity in the upright orientation. Still, there was a significant difference in matching accuracy between the upright and supine orientations at 90 and 110 degrees of humeral elevation. Subjects were more accurate when seated upright. This finding contradicts the idea of matching based on joint angle in a couple of ways. First, if subjects were matching based on joint angle, we would expect to see similar vector errors at 90 degrees of humeral elevation between the upright and supine orientations. This was not the case. Secondly, because subjects were more accurate at all elevations in the upright orientation, and activity of the anterior deltoid was greater at all elevation in the upright orientation it is likely that muscle activity, and not joint angle, was the significant contributing factor to matching accuracy.

Still, it is possible that the differences we observed have less to do with joint angle and more to do with being placed in an unfamiliar position. Variable error was significantly larger in the supine orientation, which implies that our subjects were unsure of their arm placement. One possible explanation for this observation is that tilting subjects back 90 degrees from vertical is enough to sufficiently alter normal operation in the gravitational field. This effect is likely similar to those studies where subjects match in a reduced or neutral gravitational environment. In these conditions, the centrally derived effort signal provides very little, if any, additional positional information (Ansems et al., 2006; Gooey et al., 2000). And, similar to our findings, this results in subjects becoming less consistent with their matching performance. Still, we did not remove the effects of gravity; instead we attempted to alter it by putting subjects on their backs. Because humans spend most of their active lives in an upright or vertically oriented position it is also possible that, by putting subjects on their backs, we create a situation sufficiently different from daily life that it causes the motor command sent out to execute the elevation task to either over- or under-shoot the target position. Currently, it is believed that the CNS uses a forward model to compare predicted sensory input, obtained from efference copies of the motor command, with actual sensory input to estimate current and future placement and movement of the limb (Bays & Wolpert, 2006; Branch Coslett et al., 2008). If the motor command does not accurately meet the demands of the task, a disparity results between it and the real-time proprioceptive feed, which can result in greater matching errors, and is likely a contributing factor to our results.

For the upright orientation in this study, a general trend of increasing muscle activity and decreasing matching error occurred as joint angle increased. However, we found the highest accuracy at 110 degrees (although it was not significantly different from 90 degrees) which is contrary to much of the literature (Chapman et al., 2009; King, Harding, & Karduna, 2013; Suprak et al., 2006). This difference could be attributable to several factors. The subjects in our study performed the repositioning tasks while seated in a chair that had minimal neck and back support. It is well known that tactile stimulation increases the perception of movement (Collins & Prochazka, 1996; Collins, 2005). We attempted to limit the amount of cutaneous stimulation by providing limited support to the torso and head while allowing the scapula to move freely. Still, stretch, even far from a joint, can be sufficient enough to cause stimulation of cutaneous receptors surrounding the joint (Edin, 2001). Tactile stimulation is likely greater in the supine condition due to the greater compressive effect of gravity on the torso in this orientation, which likely increases stimulation of the mechanoreceptors in the skin. This might help to explain some of the increase observed in vector error. And while there was not a significant decrease in vector error with elevation, the data shows a trend towards decreasing error, likely because the stretch is at its greatest with 110 degrees of humeral elevation. It is worth noting that while subjects matched at 80 degrees anterior to the frontal plane, it is unlikely that stretch of the posterior joint capsule had any effect on repositioning accuracy since JPS has not been shown to increase near the end ranges of motion (where capsular stretch is greatest) in unconstrained repositioning tasks (Suprak, 2011).

It is often assumed that muscle activity is greater due to resistive torque. Our assumption, that greater EMG activity means greater muscle activation (and therefore, greater muscle spindle co-activation through the fusimotor system) (Gooey et al., 2000; McCloskey, 1973), is overly simplistic. Activity in a muscle can be altered due to a variety of mechanisms, such as changes in the muscle moment arm (Ackland, Pak, Richardson, & Pandy, 2008), muscle line of action (Ackland & Pandy, 2009), and differences in kinematics between the scapula, humerus and clavicle (Braman, Engel, LaPrade, & Ludewig, 2009). Still, our data showed anterior deltoid activation levels similar to those seen in other studies (Escamilla, Yamashiro, Paulos, & Andrews, 2009). Greater activity in the deltoid group correlates to an increase in activity of all those muscles that cross the shoulder, especially the rotator cuff (Escamilla et al., 2009; Ludewig, Cook, & Nawoczenski, 1996). This increases in muscle activation would theoretically heighten the population signal of the afferents surrounding the glenohumeral joint, which has been shown to be key to the proper computation of JPS (Ribot-Ciscar & Roll, 1998; Ribot-Ciscar, Bergenheim, Albert, & Roll, 2003). Along these lines Suprak et al. (2007) found that JPS increased under conditions of increasing external load. Again, these data support the idea of muscle activation levels being critical to JPS accuracy.

Summary

According to the data subjects match with greater accuracy and less variability in an upright compared to a supine orientation. Anterior deltoid muscle activity increases with humeral elevation in the vertical plane and correlates with decreased vector error scores. This data when taken together supports the torque hypothesis, which says that vector error decreases with increased levels of muscle activation as modulated by resistive torque.

Chapter V

Summary, Conclusions, and Recommendations

Summary

The body of literature surrounding joint position sense continues to grow. Today it is understood that JPS is determined from a combination of peripheral and central mechanisms. There are many mechanoreceptors that contribute to the determination of JPS, including those that lie in the joint (Ruffini nerve endings and Pacinian corpuscles), muscles and skin (Collins, 2005; Jami, 1992; Steinbeck et al., 2003; Voight et al., 1996). However, peripherally it is believed that the muscle spindle is the primary kinesthetic sensor, responsible for providing information back to the CNS regarding joint position and segment movement velocity (Proske & Gandevia, 2009; Proske, 2006; Winter et al., 2005). This hypothesis is widely accepted and well supported through the muscle vibration and thixotropy studies (Allen et al., 2006; Ansems et al., 2006; Goodwin et al., 1972; Gooey et al., 2000; Proske et al., 1993; Walsh et al., 2009). Still, a single muscle spindle will not provide the CNS with much meaningful information about the position or movement parameters of a limb. Instead, information from the whole afferent population from a diverse array of mechanoreceptors is used to determine the location and speed of movement for the segment and joint of interest, a phenomenon that has been termed population coding (Bergenheim et al., 1996; Bergenheim, Ribot-Ciscar, & Roll, 2000; Cordo et al., 2002; Ribot-Ciscar et al., 2003). However, all of the peripheral mechanisms have their influence at the level of the CNS, which itself can influence JPS. The most studied central mechanisms are motor/central commands and the sense of effort. In proprioception involving limb muscles, judgments of force and of heaviness of lifted weights have been shown to depend not only on afferent signals about force but also on signals of central origin associated with the level of perceived force. Such sensations are usually termed signals of central/motor command or effort (Gandevia et al., 2006). More specifically the term “sense of effort” came from the observation that subjects matched the effort required to achieve a given force and not the forces themselves (Winter et al., 2005). These central commands combine with afferent information to contribute to the overall computation of JPS (Smith et al., 2009).

When studying JPS, it is important to understand the common methods used. Until recently it has been common place to use passive paradigms. The two most commonly used passive methods were the threshold to detection of passive motion (TTDPM) and the reproduction of passive positioning (RPP). While these procedures have been critical to furthering our understanding of JPS they ignore a critical component, the active nature of human movement. This is why active matching and repositioning paradigms have gained popularity in the literature. Such tests allow for the measurement and study of JPS in a more functional setting. Using this method transducers are attached to the segments of interest and the subject is placed in a small magnetic field so three dimensional kinematics can be recorded. These studies have opened up new areas and created more difficult questions. One such question revolves around something called the torque hypothesis. This hypothesis says that increasing levels of resistive torque and therefore increasing muscle activation increase JPS acuity. This hypothesis has been supported through a number of studies that found an increase in JPS acuity with progressive humeral elevation up to 90 degrees (the position with the greatest action of gravity) (King et al., 2013; King & Karduna, 2014; Suprak et al., 2006, 2007). However, a study conducted by Chapman et al. (2009) attempted to uncouple joint torque from elevation by tilting their subject’s trunks back 45 degrees from vertical. They found that elevation angle played a greater role in modulating JPS than joint torque.

Chapman's article provided valuable information regarding how body position and joint torque alter JPS. We wanted to take his work further by exaggerating the amount of body tilt. It seemed logical to tip subjects back a full 90 degrees. Along with testing subjects in both upright and supine orientations, we selected 90 degrees of humeral elevation specifically because this position would have the greatest theoretical amount of muscle activation in the upright condition (due to the segment being approximately perpendicular to the gravitational field) while simultaneously having the least amount of muscle activation in the tilted or supine condition (due to the segment being approximately parallel with the gravitational field). This way, we could keep the joint angle constant while altering the joint torque, and therefore the level of shoulder muscle activation. This would help us better determine if muscle activation or joint angle is more important to the computation of JPS. Specifically our hypothesis was that segment angle would play a larger role in determining JPS acuity than muscle activation with humeral elevation up to 90 degrees. Experimentally, therefore, JPS acuity would be the most accurate at 90 degrees of humeral elevation in both the seated and supine positions, regardless of the torque due to gravity.

For our study we had subjects attempt to recreate presented positions at 70, 90 and 110 degrees of humeral elevation both while upright on a custom made chair, or supine on the same chair. Subjects completed a total of 3 trials at each angle for a total of 9 trials. They did this for the two orientations (upright and supine) for a total of 18 trials. Starting position and humeral elevation angles were randomized. Data from 35 subjects were used in a two way repeat measures ANOVA to compare the two conditions with the three elevation angles.

Conclusions

The current experimental hypothesis was rejected, in that joint angle did not appear to discriminate joint position with more accuracy compared to torque and muscle activity. On the contrary, we found that shoulder muscle activity level likely played a greater role in JPS determination since shoulder muscle activity increased linearly with humeral elevation angle and positively correlated with decreased repositioning errors in the upright orientation. Similar to past research we found that JPS accuracy increased with humeral elevation, but only in the upright condition. We also found that anterior deltoid muscle activity increased with progressive humeral elevation, but again only in the upright condition. There was a significant difference in both matching error and muscle activity levels between the upright and supine conditions. This data, when taken together supports the role of muscle activation in JPS acuity and supports the torque hypothesis.

Recommendations

Future Research. As the mechanisms regulating JPS have not yet been fully elucidated, more research is needed in this area. Specifically more research is needed to investigate how the position of an active limb is determined in three dimensions. Future research also needs to focus on the torque hypothesis as well as joint angle and their contributions to JPS.

Since we only used a subset of our study population to determine the activation levels of the anterior and posterior deltoid muscles during active repositioning it would be beneficial to use a larger number of subjects. Also, we used anterior and posterior deltoid muscle activity as a proxy for whole shoulder muscle activity. Because JPS appears to be determined from the whole population of afferents surrounding a joint it would be beneficial to study more than just these two muscles.

One advantage of passive tests restricted to the sagittal plane is that it is easier to alter the effects of gravity. It would be beneficial to see how altering gravity by either counterweighting the subjects arm or placing them in a gravity neutral or decreased gravitational situation would affect matching accuracy and uncertainty. Muscle activity and joint angle likely both contribute to JPS acuity. By placing subjects in an altered gravitational situation it might help to elucidate which mechanisms contribute more to JPS in an unconstrained repositioning test.

Another important area of JPS that has not been well studied in the active unconstrained paradigms is how muscle fatigue and the sense of effort modulate matching accuracy. While muscle activation appears to be critical to JPS accuracy, too much muscle activity, resulting in fatigue, is likely to mitigate any of the positive effects since muscle fatigue has been shown to greatly decrease matching accuracy and increase uncertainty on simple active constrained tests (Allen et al., 2006; Carpenter et al., 1998; Walsh et al., 2004).

Practical Applications. The ability for an individual to properly determine the location of their limbs in space is critical to both athletic and daily activities. In both the clinic and the gym, understanding how JPS is determined can lead to better exercise selection that enhances proprioception. Our data points to muscle activity as being critical to JPS accuracy. Simply put, subjects are likely to perform shoulder exercises with better proprioceptive input in an upright position with the arms elevated around 90 to 110 degrees.

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Appendix A

Human Subjects Activity Review

1. ***What is your research question, or the specific hypothesis?***

Specific Aim: The purpose of this study is to investigate the effects of shoulder elevation and body posture (upright and supine) on shoulder repositioning errors (absolute and variable). Based on what have seen in the literature our hypothesis is that segment angle will play a larger role in determining JPS acuity than resistive torque (as approximated by the angle of the segment with respects to gravity) with humeral elevation up to 90 degrees. Experimentally, therefore JPS acuity will be the most accurate at 90 degrees of humeral elevation in both the seated and supine positions, regardless of muscle activation.

2. ***What are the potential benefits of the proposed research to the field?***

The stability of our joints relies heavily on feedback loops involving mechanoreceptors in the muscles (Banks et al., 2009; Banks, 2006; Swash & Fox, 1972), skin (Johansson & Vallbo, 1979; Kennedy & Inglis, 2002) and joints (Gerhardt et al., 2012; Steinbeck et al., 2003) that are integrated with the central nervous system (CNS) as well as the degree of bony congruity and integrity of capsuloligamentous supporting structures (Nyland et al., 1998). In the shoulder specifically, where a large amount of mobility comes at a detriment to stability, proper communication between mechanoreceptors in the periphery and the CNS is crucial to the maintenance of accurate position sense. Joint position sense (JPS) is determined in the CNS from the combination of peripheral information from joint receptors, muscle spindles and Golgi tendon organs (Riemann & Lephart, 2002b) as well as central mechanisms such as motor commands and the sense of effort (Allen et al., 2006; Gandevia et al., 2006; Smith et al., 2009; Voss et al., 2006; L. D. Walsh et al., 2010; Winter et al., 2005).

Historically, both active and passive matching paradigms have been used to delineate the multitude of mechanisms involved in JPS. Two of the most common methods for studying JPS in the orthopedic literature are the threshold to detection of passive motion (TTDPM) and the reproduction of passive positioning (RPP). In TTDPM test the joint is passively rotated from a starting position with the use of a mechanical device, and the blindfolded subject indicates when they first detect motion, usually by pushing a button on a trigger that stops the machine. The passive nature of the procedure is thought to selectively stimulate mechanoreceptors in the joint structures (Lephart et al., 1998). In RPP testing, the joint is rotated, usually passively, through a range of motion to a specific target angle. The subject holds the target angle for a period of time before returning to the start position. The subject then actively or passively attempts to replicate the presented angle. In passive modes the joint will be moved through the range of motion by a mechanical apparatus and the blindfolded subject indicates when they believe they have accurately replicated the presented angle, usually by pressing a button on a trigger that stops the testing apparatus. This testing method is thought to assess the function of mechanoreceptors in the joint as well as Golgi tendon organs and muscle spindles (Lephart et al., 1998). Proprioceptive acuity tested using TTDPM and RPP has been shown to be diminished in those people suffering from joint injury (Lephart et al., 1994; Machner et al., 2003; Warner et al., 1996). In order to better understand how active segments perform in matching tasks, researchers started to use bilateral active matching tasks where one limb is placed in a specific position (called the reference limb) that the subject than attempts to match with their other, free limb (indicator limb). This type of test is typically isolated to a single joint such as the wrist, knee, elbow or shoulder. More recently active unconstrained repositioning tests (AUR) have been used to more functionally study JPS.

Unconstrained active paradigms allow subjects to move their limbs in all three dimensions without altering or restricting their natural range of motion (ROM). These types of tests allow for measurements of JPS in a much more functional setting. Using this method, transducers are attached to the segments of interest and the subject is placed in a small magnetic field so three dimensional kinematics of the involved segments can be recorded. This method has been found to be a valid and non-invasive means of determining kinematics in the upper extremities (Karduna et al., 2001).

Unconstrained unilateral active repositioning paradigms have shown that JPS acuity increases with arm elevation up to 90°, and decreases thereafter (Suprak et al., 2006). One hypothesis surrounding this observation implicates the role of gravity in altering the torque on the joint due to the change in the external moment observed with arm elevation up to 90 degrees. Furthermore, the addition of weight during a similar unconstrained matching task improved matching accuracy, which is indicative of both muscle activation levels as well as motor command signals improving JPS acuity (Suprak et al., 2007). However, when Chapman, Suprak and Karduna (2009) attempted to uncouple joint angle from joint torque they found that matching based on elevation angle demonstrated no significant difference, while matching based on torques did result in differences. This finding implies that elevation angle at the shoulder may play a more important role in modulating JPS than joint toque. However, the extent to which both joint torque and shoulder elevation angle contribute to JPS remains to be determined. Therefore, it is the goal of this study to further examine the relative contribution of resistive torque and joint angle on JPS acuity by having subjects match in a vertical and supine position such that the same relative angles for the arm are tested in each posture. In this way, joint angle with respect to the thorax will remain the same while joint torques will be altered.

It is our hope that this study will lend insight into the understanding of the mechanisms underlying joint stability. Improved shoulder JPS under conditions of either increased muscle activation or joint angles may signify a strategy for avoiding injury while maintaining coordinated movement patterns during functional activities involving high forces, since these are the types of activities in which joint injuries are the most likely to occur. The better we understand how shoulder JPS changes under conditions of increased muscular activation and progressive elevation, the better we may be able to guide clinicians in selecting functional rehabilitation exercises with external loads or in positions of increased external torque to promote joint stability during movement.

3. ***What are the potential benefits, if any, of the proposed research to the subjects?***
Individual subjects within this study will gain no direct benefits.

4. ***Answer a), then answer either b) or c) as appropriate.***

a. ***Describe how you will identify the subject population, and how you will contact key individuals who will allow you access to that subject population or database.***

Subjects will be recruited from within the Western Washington University Physical Education, Health and Recreation department.

b. ***Describe how you will recruit a sample from your subject population, including possible use of compensation, and the number of subjects to be recruited.***

The population for this study will consist of 30 healthy male and female subjects (15 male, 15 female) who will be recruited from Western Washington University PEHR department. Subjects will be included in the study only if they had full shoulder ROM in scapular plane elevation and no history of upper extremity or thoracic spine injury within the past six months. If the subjects could not finish the testing they were removed from the study.

5. ***Briefly describe the research methodology. Attach copies of all test instruments/questionnaires that will be used.***

Instrumentation:

Kinematic data will be collected using the Polhemus Fastrak 3Space magnetic tracking system (Colchester, VT), which consists of a transmitter, three receivers and a digitizer. To track the movement of the humerus with respect to the thorax during testing, one receiver will be taped on the sternum, approximately 1.5 cm inferior to the jugular notch (Borstad & Ludewig, 2002), and one on the humerus, just above the lateral epicondyle, secured with a custom-molded Orthoplast cuff and Velcro strap. In addition, one receiver will be fastened to the acromion process for digitization purposes, but will be removed prior to testing (Karduna et al., 2001). Following attachment of the receivers, with the subject standing, various bony landmarks will be digitized on the thorax and humerus in order to establish the anatomical coordinate systems, in accordance with the standard endorsed by the International Society of Biomechanics (Wu et al., 2005). The body segments and corresponding digitization points will be as follows, thorax: C7, T8, jugular notch, and xiphoid process; humerus: medial epicondyle, lateral epicondyle, and humeral head. The center of the humeral head will be calculated using a least squares algorithm and is defined as the point that moved the least during several small arcs of motion (Harryman et al., 1992). In order to estimate muscle activation levels around the glenohumeral joint electromyography (EMG) will be used (Noraxon TeleMyo DTS Desk Receiver System, Scottsdale, Arizona) and electrodes will be placed on both the anterior and posterior deltoid muscles of each subject's dominant arm.

Measurement Techniques and testing procedures:

All data collection will take place in the Motor Control Laboratory at Western Washington University. All testing will be completed in a single session and performed on the dominant upper extremity. Subjects will complete an injury history form which also included personal information such as age, height and weight (self-reported), arm dominance, defined as the arm used to throw a ball and current activity level prior to testing. All testing will be completed in a single session. Prior to testing the subjects will complete a standardized warm-up including Codman's pendulums and stretches for the rotator cuff muscles. Codman's pendulum exercises will be performed with subjects bent over with the non-dominant hand on a table, and holding a 2.5-lb. weight in their dominant hand, letting the weight hang down at arm's length. Subjects will perform one set of 15 repetitions of arm circles, both clockwise and counterclockwise, followed by one set of 15 repetitions of a back and forth movement in the sagittal plane. Stretches will consist of holding a static external and then internal rotation position, both with the shoulder abducted to approximately 90˚, for two sets of 15 seconds each. Following the warm-up procedure subjects removed their shirts (females wore sports bras) and all jewelry in order to restrict tactile cues during testing. Subjects were seated on a custom made bench with back support so that there would be equivalent and minimal tactile stimulus in the seated and supine positions.

Subjects will be asked to sit on the bench facing forward with the torso erect and flat against the adjustable backing. While maintaining this trunk and head position subjects will elevate their humerus to 70°, 90° and 110° in the sagittal plane with respect to the thorax, as confirmed with a real-time display of plane and elevation angles via custom-written LabView software. After subjects perform matching tasks for the three elevation angles in the upright position the bench was adjusted such that the subjects will be moved 90° back from a sitting position to a supine position. Subjects again elevate the humerus to 70°, 90° and 110° in the sagittal plane with respect to the thorax.

The testing protocol will be thoroughly explained to the subjects while watching the visual output, first on the computer, then through the head-mounted display. A gray scale with a black square in the center is presented to the subject, via custom written LabView software. The black square represents the target position for a given trial. On the four sides of the screen, rectangular boxes appeared in order to prompt subjects as to which direction to move their arm in order to arrive at the target position.

All trials begin with the arm at the side. Subjects will be instructed to move their arms in the direction of the rectangular boxes. When the actual shoulder position is within five degrees of the target position in both plane and elevation angles, all of the boxes disappear and a red dot appears on the screen, representing the instantaneous shoulder position. Subjects will continue to position their arm until the red dot on the screen is inside the black square, indicating that the shoulder is in the target position. The borders of the square represented a boundary of 1° in either direction from the target position, with respect to the plane and elevation angles. Once the shoulder is in the target position for one second, an audible "beep" will be heard and the screen will turn black and remain that way for the rest of the trial. Subjects will be instructed to maintain their shoulder in the target position for a five second period, during which time they will concentrate only on the position of the shoulder. After the subject has maintained the target position for five seconds, a computer generated voice instructs the subject to "relax", at which time the subject will lower the arm back to the side.

Three seconds after the arm is returned to the side, another computer generated voice instructs subjects to "return". Subjects then attempted to replicate the presented target position in both plane and elevation angles. When subjects perceive that their shoulder is at the target position, they use the contralateral hand to push a trigger button interfaced with the computer in order to time-stamp the reproduced position. Subjects will be instructed to maintain the shoulder in the reproduced position for one second after pushing the trigger button, at which time an audible "beep" sounds and the trial ends.

During all trials, subjects will be instructed to keep their backs straight and face forward while in the seated position. Verbal corrections will be offered if posture changes at any time during testing. Therefore, although the visual display provides cues to aid subjects in reaching the target position for each trial, the target position will always seen by the subjects as being straight ahead in their visual field. The visual display will, therefore, not provide useful information for subjects in determining the shoulder position. The procedure will be explained and demonstrated to subjects, first while viewing the visual output on the computer screen, and then through the head-mounted display until the subjects felt comfortable with the process. Prior to the start of testing, subjects will perform several practice trials (at least five) at a target position consisting of a plane 45° anterior to the frontal plane and 60° of elevation. The practice trials will be repeated until subjects feel comfortable and confident in performing the task.

In order to address the effects of shoulder position in the vertical plane on unconstrained JPS in both the seated and supine positions three angles will be selected in order to vary the amount of external torque. These positions included the plane angles 70°, 90° and 110° of elevation, all in a plane 80 degrees anterior the frontal plane. Within each trial sequence, each of these three positions will be tested three times, for a total of nine trials. These trials are automated by the software, and separated by a 15-s rest interval. The target angles and seated/supine positions will be presented in a randomized order, according to a balanced Latin square design (Portney & Watkins, 2000). Subjects will complete two sequences of these nine trials, separated by five minutes.

6. ***Give specific examples (with literature citations) for the use of your test instruments/questionnaires, or similar ones, in previous similar studies in your field.***

Measuring kinematics with a magnetic tracking device has been used extensively in the research field. Suprak, Osternig, van Donkelaar and Karduna (2006) used a Polhemus 3space magnetic tracking system to measure unconstrained unilateral active repositioning with arm elevation in healthy college students. In addition to arm elevation, Suprak, Osternig, van Donkelaar and Karduna (2007) used the same magnetic tracking system to look at how the addition of weight during unconstrained matching task affected matching accuracy. In 2009 Chapman, Suprak and Karduna again used the 3space magnetic tracking system in a study that attempted to uncouple joint angle from joint torque. The use of a magnetic tracking device has been particularly useful in illustrating the differences in JPS matching accuracy between active and passive conditions (Erickson & Karduna, 2012; You-jou Hung & Darling, 2012).

7. ***Describe how your study design is appropriate to examine your question or specific hypothesis. Include a description of controls used, if any.***

In the literature, there is conflicting evidence, some of which supports the roll of increased muscle activation (resistive torque) as a prime determinate of JPS acuity (Suprak et al., 2007). Other research points to the position of the humerus with respect to the thorax as being a determinate of JPS acuity (Chapman et al., 2009; Suprak et al., 2006). By testing subjects in a seated and supine position we will effectively be reversing gravity. If we see no changes in repositioning accuracy at 90 degrees of humeral elevation in both seated and supine positions we will support our hypothesis which gives important information regarding the mechanisms involved in the determination of JPS.

8. ***Give specific examples (with literature citations) for the use of your study design, or similar ones, in previous similar studies in your field.***

Our study is being modeled after research done by Chapman et al. (2009), Erickson and Karduna (2012), Suprak et al. (2006, 2007) and Suprak (2011).

9. ***Describe the potential risks to the human subjects involved.***

Because multiple trials will be performed, there is a risk of developing muscle fatigue.

10. ***If the research involves potential risks, describe the safeguards that will be used to minimize such risks.***

To minimize the risk of muscle fatigue, rest periods of 15 seconds following each trial, and 10 minutes between trial sequences will be employed.

11. ***Describe how you will address privacy and /or confidentiality.***

Each subject will be assigned a unique subject number. Only the principal investigator and his faculty advisor will have access to information matching particular data sets to individual subjects. For example, subject IDs will appear similar to that below:

TJPS17R

The above code indicates that this subject was involved in the study of the effects of body tilt and humeral elevation angle on joint position sense (TJPS), that he/she was the 17th subject tested (17), and that his/her right shoulder was tested (R).

12. ***If your research involves the use of schools (pre-kindergarten to university level) or other organizations (e.g., community clubs, companies), please attach a clearance eletter from an administrator from your research site indicating that you have been given permission to conduct this research. For pre-kindergarten to grade 12 level schools, an administrator (e.g. principal or higher) should issue the permission. For post-secondary level schools the class instructor may grant permission. For Western Washington university, this requirement of a clearance letter is waived if you are recruiting subjects from a scheduled class. If youa re recruiting subjects from a campus group (not a class) at Western Washington University, you are required to obtain a clearance letter from a leader or coordinator of the group.***

N/A

13. ***If your research involves the use of schools (pre-kindergarten to university level)or other organizations (e.g., community clubs, companies), and you plan to take still or video pictures as part of your research, please complete***

a) To d) below:
a. Who have you contacted at the school distric or organization involved, to determine the policy on the use of photography in the school or organization?
b. Explain how your research plan conforms to the policy on the use of photography in the school or organization.
c. Attach a copy of the school distric or organization policy on the use of photography at the schools or organization.
d. Explain how you will ensure that the only people recorded in your pictures will be the ones that have signed a consent form.

N/A

1. ***A current curriculum vitae.***

See attached

2. ***A copy of the certificate of completion for Human Subjects Training from the online human subjects training module, for each person involved in the research who will have any contact with the subjects or their data.***

See attached

3. ***If your subjects are required to turn in a physical clearance from priot to participation include a copy of the blank form.***

N/A

Appendix B

Informed Consent

Western Washington University
Consent to Take Part in a Research Study
Project: The Effect of Tilt on Shoulder Joint Position Sense

You are invited to participate in a research study conducted by Jordan Sahlberg, Graduate Student, from the department of Physical Education, Health, and Recreation at the Western Washington University. The purpose of this investigation is to study the ability to actively reposition the shoulder in three previously presented active target position while seated upright in a chair and while seated supine in the same chair. You were selected as a possible participant in this study because you have no history of shoulder pathology.

If you decide to participate, you understand that the following things will be done to you. You will be asked to fill out a brief form to provide basic information such as age, height and weight and which arm is your dominant arm. Non-invasive measurements will be made throughout the experiment. To perform these measurements, small sensors will be attached by straps or tape to your arm, breastbone and shoulder. You will be asked to actively position your shoulder in a specified target position, with the aid of a moving cursor on a head-mounted display screen, corresponding to the location of your arm in space. You will then be asked to attempt to replicate the presented angle without the benefit of visual feedback. Several different target positions will be attempted. You will also be asked to perform simple arm elevation. All of this will be done seated and again while supine. The entire testing process should take about 90 minutes.

There is no direct benefit to you by participating in this study. However, you understand that information gained in this study may help in the understanding of the function of the shoulder.

Participation in any research study carries with it possible risks. Because multiple trials will be performed, there is a risk of muscle fatigue. However, precautions have been taken to minimize this risk. However, you may discontinue participation at any time during testing.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Subject identities will be kept confidential by coding the data with subject numbers, rather than names. You will be given the opportunity to give written consent to be contacted in the future for the purpose of follow-up regarding this project.

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

If you have any questions regarding the project procedures, please feel free to contact Dave Suprak, (360) 650-2586, Department of Physical Education, Health and Recreation, Western Washington University, Bellingham, WA, 98225. If you have questions regarding your rights as a research subject, or if you should suffer any research-related adverse effects, contact Janai Symons in the Office of Research and Sponsored Programs, Western Washington University, Bellingham, WA, 98225, (360) 650-3082. You have been offered a copy of this form to keep.

Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you have received a copy of this form, and that you are not waiving any legal claims, rights or remedies. The signature below indicates that the participant is 18 years of age or older.

Print Name____

Signature____

Date_________________________

Appendix C

Research Protocol Checklist and Data Logging

	Check Off List			Comments
Date				Common Activities:
Time (Begun, Completed)				
Subject Number				
Height (in)				
Body Weight (lb)				
Age (yr)				
Gender	Male / Female			
Arm Tested	L / R			Injury History:
Consent Form Completed	Yes / No			
Beighton Hypermobility Scale completed	Yes / No			
Warm-up Completed	Yes / No			
Mark Key Landmarks	Yes / No			
Prep Skin Sites	Yes / No			
Stool Height Adjusted	Yes / No			
Sternal Sensor Attachment	Yes / No			
Scapular Sensor Attachment	Yes / No			
Humerus Sensor Attachment	Yes / No			
Transmitter Height Adjusted	Yes / No			
Digitize Bony Landmarks	Yes / No			
Humeral Head Translation (mm)				
Scapular Digitization Value (deg.)				
Subject Matrix Obtained	Yes / No			
Check Motion	Yes / No			
Scapular Sensor detached	Yes / No			
Check Motion/Calculate ROM	Yes / No			End ROM:
Enter subject number into labview	Yes / No			
Load position sequence	Yes / No			
Lock Stool Position	Yes / No			
Explain Procedure (w/ screen, w/ goggles)	Yes / No			
Show "Too Much Variance"	Yes / No			

Trial Position Sequence:

Upright / Supine	Upright / Supine	Pads:			Mistakes		
		Upright	Blue	Black	Test 1	Test 2	Test 3
		# Under Shank					
1	1	# Under glutes					
2	2	**Supine**					
		# Under shank					
3	3	# Under glutes					
4	4						
5	5						
6	6						
7	7						
		EMG Collection:					
8	8						
		Load EMG sequence	Yes / No				
9	9	check EMG	Yes / No				
		MVC					
		Turn kinematics off	Yes / No				
		Adjust time series to 7 seconds	Yes / No				
		Save file	Yes / No				

Joint	Criteria	Score
Little Finger	Passive dorsi beyond 90 deg	
Right		
Left		
Thumb	Passive dorsi to flexor aspect	
Right	of forearm	
Left		
Elbow	Hyperextension > 10 deg	
Right		
Left		
Knee	Hyperextension > 10 deg	
Right		
Left		
Trunk	Palms rest flat on floor	
	Total	

* 1 point for each item performed successfully.

* ≥ 4 = High generalized joint laxity

< 4 = Low generalized joint laxity

Appendix D

Table 2.

Raw data for subject characteristics

Subject #	**Sex**	**Age**	**Dominate side (R or L)**	**Weight (lbs)**	**Weight (kg)**	**Height (inches)**	**Height (m)**
TJPS01	F	21	R	131	59.42	64	1.63
TJPS02	F	24	R	144	65.32	67	1.70
TJPS03	F	22	R	218	98.88	69	1.75
TJPS04	F	22	R	176	79.83	69	1.75
TJPS05	F	23	R	160	72.57	67	1.70
TJPS06	M	28	R	183	83.01	72	1.83
TJPS07	M	26	R	161	73.03	71	1.80
TJPS08	M	25	R	221	100.24	72	1.83
TJPS09	M	24	L	163	73.94	70	1.78
TJPS10	F	25	R	147	66.68	65	1.65
TJPS12	F	21	R	162	73.48	73	1.85
TJPS13	F	22	R	138	62.60	65	1.65
TJPS14	M	35	R	145	65.77	68	1.73
TJPS15	F	21	R	116	52.62	69	1.75
TJPS16	F	21	R	151	68.49	68	1.73
TJPS17	F	22	R	227	102.97	70	1.78
TJPS18	M	22	R	168	76.20	70	1.78
TJPS19	F	21	R	108	48.99	61	1.55
TJPS20	F	21	R	147	66.68	66	1.68
TJPS22	F	21	L	140	63.50	64	1.63
TJPS24	F	20	R	134	60.78	64	1.63
TJPS25	F	22	R	139	63.05	68	1.73
TJPS26	F	21	R	136	61.69	65	1.65
TJPS27	F	22	R	128	58.06	64	1.63
TJPS28	F	21	R	135	61.23	68	1.73
TJPS29	F	29	R	194	88.00	64	1.63
TJPS30	F	22	R	135	61.23	68	1.73
TJPS31	F	24	R	155	70.31	64	1.63
TJPS32	F	20	R	127	57.61	65	1.65
TJPS33	M	24	R	182	82.55	72	1.83
TJPS34	M	26	R	207	93.89	73	1.85
TJPS35	F	22	R	78	35.38	60	1.52
TJPS36	F	22	R	126	57.15	63	1.60
TJPS37	F	21	R	158	71.67	69	1.75
TJPS38	F	22	R	163	73.94	71	1.80
Average		23.00		154.37	70.02	67.37	1.71
SD		2.99		32.27	14.64	3.40	0.09
SEM		3.89		26.09	11.84	11.39	0.29

Table 3.

Raw data for vector error

	Upright Vector Error			**Supine Vector Error**		
Subject #	**80/70**	**80/90**	**80/110**	**80/70**	**80/90**	**80/110**
TJPS01	3.87	5.32	3.8	7.54	5.24	6.96
TJPS02	6.2	5.2	1.9	8.59	7.63	10.41
TJPS03	4.53	4.32	8.93	8.23	6.5	9.44
TJPS04	4.95	7.46	5.04	6.97	4.46	6.26
TJPS05	6.42	5.76	3.07	1.67	10.11	6.28
TJPS06	5.76	3.41	4.23	3.67	3.66	6.9
TJPS07	5.04	4.31	3.19	6.39	5.26	6.73
TJPS08	7.14	6.16	4.77	5.13	7.77	9.18
TJPS09	6.38	4.18	3.69	6.55	4.57	8.12
TJPS10	9.65	4.49	5.49	4.88	5.6	9.19
TJPS12	4.02	3.41	5.17	4.95	10.58	7.58
TJPS13	2.12	2.31	3.51	4.85	6.93	7.26
TJPS14	5.28	5.16	5.84	4.65	5.28	7.22
TJPS15	4.78	7.62	6.01	4.29	1.32	3.52
TJPS16	5.54	5.86	6.4	4.36	6.46	12.71
TJPS17	8.05	4.02	3.58	6.77	4.33	5.16
TJPS18	5.5	3.65	3.91	7.02	12.51	7.84
TJPS19	5.83	2.64	3.81	7.19	13.06	8.52
TJPS20	5.83	4.67	4.55	10.45	5.45	7.58
TJPS22	9.06	5.44	5.69	4.81	11.18	12.49
TJPS24	10.83	6.47	3.13	8.1	7.7	7.19
TJPS25	7.11	9.23	5.59	15.28	4.42	8.21
TJPS26	10.87	6.38	3.36	7.4	8.28	8.04
TJPS27	7.48	2.62	2.97	9.78	14.25	5.48
TJPS28	6.26	3	1.83	10.94	7.8	4.92
TJPS29	2.79	3.42	3.14	3.56	6.56	8.2
TJPS30	6.61	4.14	3.93	3.97	7.09	13.17
TJPS31	12.92	6.63	5.54	3.9	4.32	15.1
TJPS32	12.37	5.63	3.58	18.17	4.05	5
TJPS33	3.42	3.64	4.05	2.86	12.07	4.86
TJPS34	7.93	7.15	4.91	5.62	4.45	10.32
TJPS35	4.77	3.69	2.14	5.94	7.29	4.56
TJPS36	13.66	2.2	4.16	9.88	3.58	11.74
TJPS37	9.53	10.24	6.65	2.41	5.03	6.59
TJPS38	4.5	5.35	4.01	7.72	3.02	8.89
Average	6.8	5.0	4.3	6.7	6.8	8.0
SD	2.83	1.88	1.46	3.40	3.09	2.65
SEM	0.48	0.32	0.25	0.57	0.52	0.45

Table 4.

Raw data for variable error

	Upright Variable Error			**Supine Variable Error**		
Subject #	**80/70**	**80/90**	**80/110**	**80/70**	**80/90**	**80/110**
TJPS01	1.514	2.706	1.147	4.342	0.347	1.021
TJPS02	1.617	1.415	1.005	5.917	2.385	0.457
TJPS03	2.381	1.915	5.659	4.47	2.089	2.197
TJPS04	1.789	1.394	3.801	2.232	1.877	3.498
TJPS05	0.779	1.215	2.49	0.733	5.054	1.6
TJPS06	1.508	2.254	2.256	0.761	0.774	1.812
TJPS07	1.78	1.376	0.786	0.585	0.722	3.312
TJPS08	0.863	3.554	0.315	1.019	0.627	1.614
TJPS09	1.806	0.535	2.19	1.843	3.55	3.494
TJPS10	2.774	3.524	2.886	2.824	2.561	2.815
TJPS12	1.758	0.795	1.744	4.829	3.496	2.607
TJPS13	1.01	0.26	0.537	0.206	2.42	2.584
TJPS14	1.078	2.726	2.244	3.366	2.224	3.935
TJPS15	0.446	3.087	0.75	2.505	0.319	0.546
TJPS16	1.126	1.015	2.201	3.44	1.591	3.165
TJPS17	1.748	2.587	1.362	3.726	2.038	2.404
TJPS18	2.332	0.768	1.779	2.926	2.475	0.46
TJPS19	1.774	0.082	2.383	1.26	1.122	1.712
TJPS20	2.977	1.781	2.185	2.645	1.486	3.589
TJPS22	1.952	1.974	2.929	2.862	3.012	2.259
TJPS24	0.999	1.697	0.547	0.91	2.917	0.42
TJPS25	3.332	1.601	1.803	1.854	0.899	3.61
TJPS26	1.52	3.073	1.161	3.357	1.059	3.483
TJPS27	0.93	1.11	1.353	3.581	4.699	2.174
TJPS28	3.218	0.867	1.15	4.446	4.283	0.843
TJPS29	2.286	0.998	1.391	1.675	0.808	3.356
TJPS30	1.42	1.151	0.977	2.525	0.888	0.303
TJPS31	3.198	2.015	1.373	2.254	1.669	5.189
TJPS32	4.099	1.19	1.365	5.366	1.235	2.129
TJPS33	1.208	1.849	2.348	2.157	3.756	1.105
TJPS34	0.276	1.611	1.745	4.603	2.447	0.178
TJPS35	1.373	0.474	1.583	3.435	2.579	0.913
TJPS36	0.966	2.045	1.698	2.969	0.612	3.056
TJPS37	1.938	1.572	0.544	0.5	2.129	2.276
TJPS38	1.243	2.959	1.813	1.792	1.444	2.988
Average	1.74	1.69	1.76	2.68	2.05	2.20
SD	0.87	0.91	1.03	1.47	1.24	1.25
SEM	0.15	0.15	0.17	0.25	0.21	0.21

Table 5.

Raw data for Anterior and Posterior deltoid EMG

	Upright						Supine					
	70.00		90.00		110.00		70.00		90.00		110.00	
Subject #	**AD**	**PD**	**AD**	**PD**	**AD**	**PD**	**AD**	**PD**	**AD**	**PD**	**AD**	**PD**
1.00	29.36	7.01	28.34	4.03	33.16	9.25	25.86	8.48	27.29	8.71	29.83	9.31
5.00	30.73	13.35	33.22	14.37	44.54	13.06	23.85	12.26	23.87	15.92	22.97	13.90
6.00	15.10	3.80	18.87	3.86	20.87	3.91	14.17	3.88	14.74	4.07	15.13	3.70
7.00	19.91	7.40	18.39	7.45	20.00	7.81	16.16	5.62	17.84	7.32	16.60	7.31
8.00	20.93	3.85	23.83	4.30	24.63	4.30	18.90	3.71	18.81	3.48	18.30	3.75
10.00	26.34	38.02	27.35	38.29	28.67	38.37	25.53	35.29	25.29	38.25	25.23	38.29
11.00	19.17	5.97	21.37	6.17	24.44	6.40	16.46	5.60	16.67	5.52	15.37	5.65
12.00	20.24	2.27	29.42	3.39	27.91	4.48	22.90	1.27	21.79	2.07	16.22	3.51
13.00	19.38	1.71	25.71	2.66	29.04	3.71	17.29	1.28	17.50	1.47	15.81	0.75
14.00	18.89	1.31	21.05	1.45	26.08	2.07	17.53	1.33	18.92	0.71	17.78	1.24
Average	22.01	8.47	24.75	8.60	27.93	9.33	19.86	7.87	20.27	8.75	19.32	8.74
SD	5.05	10.98	4.89	11.04	7.02	10.70	4.27	10.25	4.09	11.28	5.00	11.10
SEM	1.60	3.47	1.55	3.49	2.22	3.38	1.35	3.24	1.29	3.57	1.58	3.51