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Shoulder joint position sense is not enhanced at end range in an unconstrained task

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ABSTRACT

Shoulder joint position sense (JPS) is important for maintaining stability and contributing to coordinated movements. It is provided by afferent and centrally-derived signals interpreted and integrated by the central nervous system (CNS) for subsequent use. Shoulder JPS is enhanced as the joint approaches end range of motion (ROM) in studies involving internal and external rotation with the arm supported, but this finding has not been confirmed in unconstrained movements. To address this issue, the present study examined the effect of shoulder position in the horizontal plane on JPS at a constant elevation. Twenty-three healthy individuals were recruited from a university campus. Subjects attempted to actively replicate various target positions in both plane and elevation. Target positions consisted of five positions in the horizontal plane, normalized to individual horizontal abduction ROM, at 90° of arm elevation. All target positions were tested three times, and average absolute and variable errors were analyzed for each position. No differences in either absolute (p = .312) or variable (p = .185) errors were observed between positions. These results further support the contention that the muscle spindles are a dominant source of afferent feedback regarding shoulder JPS in unconstrained movements, even approaching end ROM, when the capsuloligamentous receptors are active.

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Abbreviations: AE, absolute error; CNS, central nervous system; JPS, joint position sense; ROM, range of motion; VE, variable error.

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1. Introduction

Joint stability results from multiple factors including bony congruity, capsuloligamentous integrity, and afferent signals arising from joint and musculotendinous mechanoreceptors integrated within the central nervous system (CNS). Afferent signals arising from various sensory receptors are integrated within the CNS in a process termed proprioception (Sherrington, 1906). Proprioception has recently been described as a combination of joint position sense (JPS), the ability of a person to identify the position of a limb in space, kinesthesia, the ability to detect limb movement (Aydin, Yildiz, Yanmis, Yildiz, & Kalyon, 2001), as well as the senses of muscular tension and effort (Gooey, Bradfield, Talbot, Morgan, & Proske, 2000; Proske & Gandevia, 2009). In addition to these afferent signals, several authors have provided evidence supporting the contribution of the motor command to the appreciation of joint position and movement senses (Gandevia, Smith, Crawford, Proske, & Taylor, 2006; Smith, Crawford, Proske, Taylor, & Gandevia, 2009; Walsh, Gandevia, & Taylor, 2010). JPS is an important contributor to the maintenance of muscle stiffness and coordination about a joint and the production of smooth movements for optimal task performance while minimizing the chance for joint injury (Madhavan & Shields, 2005; Sainburg, Poizner, & Ghez, 1993). It is especially important for the function of the shoulder, where stability is sacrificed for a large range of motion (ROM) (Janwantanakul, Magarey, Jones, & Dansie, 2001), and this point is illustrated in the increasing emphasis on proprioceptive training in shoulder rehabilitation seen in the clinical setting.

Muscle spindles have been shown to be the primary contributors to JPS in the mid ranges of joint motion, where the capsuloligamentous mechanoreceptors (i.e., Ruffini endings, Pacinian corpuscles, and Golgi endings) are relatively inactive (Goodwin, McCloskey, & Matthews, 1972; Shields, Madhavan, & Cole, 2005). This supposition is supported by the pronounced detrimental effect that muscle fatigue has on JPS, both in active and passive testing paradigms (Allen, Ansems, & Proske, 2007; Lee, Liau, Cheng, Tan, & Shih, 2003; Voight, Hardin, Blackburn, Tippett, & Canner, 1996). Muscle spindles have been reported to be more highly stimulated in the presence of and following muscular contraction, as a result of the coactivation of α- and γ-motoneurons, with more intense activation being associated with more intense muscular contractions (Durbaba, Taylor, Ellaway, & Rawlinson, 2003). In practice, shoulder JPS appears to be more accurate under conditions of increasing joint torque, as imposed by both elevation angle (Suprak, Osternig, van Donkelaar, & Karduna, 2006) and external load (Suprak, Osternig, van Donkelaar, & Karduna, 2007) in an unconstrained task involving active positioning and replication of the target position, findings that may, at least in part, be explained by increasing muscle activation levels and contributions from the motor command and muscle spindle signals. Opposing results, however, were reported in studies utilizing isometric contractions of varied intensity, which indicate greater position matching error with higher contraction intensity (Smith et al., 2009; Walsh, Smith, Gandevia, & Taylor, 2009). This discrepancy in findings may be due to the important role played by the integration of afferent signals and the motor command during movement in space in deriving a perception of joint position.

Capsuloligamentous mechanoreceptors are stimulated upon deformation of their parent tissue (Blasier, Carpenter, & Huston, 1994; Grigg, 1976). Several authors have shown that these receptors are, therefore, stimulated more in the end ROM, compared to the mid ranges, due to the elongation of their parent tissues in these ranges (Burke, Gandevia, & Macefield, 1988; Salo & Tatton, 1993; Steinbeck et al., 2003; Vangsness, Ennis, Taylor, & Atkinson, 1995). This mechanism has been supported in the shoulder by various authors investigating JPS in one plane, who have reported heightened position sense as the presented angle approaches end range of external rotation (Janwantanakul et al., 2001; Rogol, Ernst, & Perrin, 1998). In contrast, this effect has not been supported in unconstrained movement. Suprak et al. (2006) reported no differences in active repositioning accuracy at various positions in the horizontal plane at 90° of elevation. However, these authors did not normalize the positions used in target positions to the individual subject ROM, and it is unknown whether subjects were at comparable points in their respective ROM at the target positions tested. Therefore, the purpose of the present study was to examine the effect of shoulder position in the horizontal plane (referred to as the plane angle), normalized to subject ROM, on JPS acuity at a constant elevation. It was hypothesized, based on our previous study results, that shoulder position would have no effect on shoulder JPS, due to the constant external torque exerted on the shoulder in all positions at the same elevation.

2. Methods

2.1. Ethical approval

All procedures followed in this study and described in this paper were reviewed and approved by the Western Washington University Institutional Review Board for the ethical treatment of human subjects, in accordance with the latest revision of the Declaration of Helsinki. Prior to participation, all subjects read and signed an informed consent form, approved by the same review board.

2.2. Subjects

Twenty-three healthy individuals (14 males, 9 females) with a mean age of 21.7 ± 1.22 years (*M* ± *SD*), a mean height of 160.46 ± 51.57 cm, and a mean body mass of 68.5 ± 25.6 kg agreed to participate in the study. Subjects were excluded from the study if they had a history of shoulder pathology requiring surgery or physical therapy, limited ROM in 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).

2.3. Instrumentation

2.3.1. Kinematics

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 (Karduna, McClure, Michener, & Sennett, 2001) for digitization purposes, but was removed prior to testing. The transmitter was positioned behind the subject and level to the thoracic receiver (Fig. 1).

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 for the thorax and humerus, in accordance with the standard endorsed by the International Society of Biomechanics (Wu et al., 2005). The coordinate systems for the thorax and humerus were established according to the protocol described by Suprak et al. (2006). 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). Euler angles were used to represent two sequence-dependent humeral rotations with respect to the thorax, consisting of the plane of elevation and degree of elevation, as described by An, Browne, Korinek, Tanaka, and Morrey (1991).

2.3.2. Head-mounted display

In order to occlude visual cues related to shoulder position, all subjects were fitted with a head-mounted display (I-O Display Systems, Sacramento, CA), modified with felt attached to the top, sides, and bottom of the display unit to eliminate the influence of external light sources. The display permitted kinematic output from the computer to be presented to subjects on a two-dimensional screen. Therefore, subjects were able to view the computer output with complete visual occlusion of the position and movement of the shoulder joint.

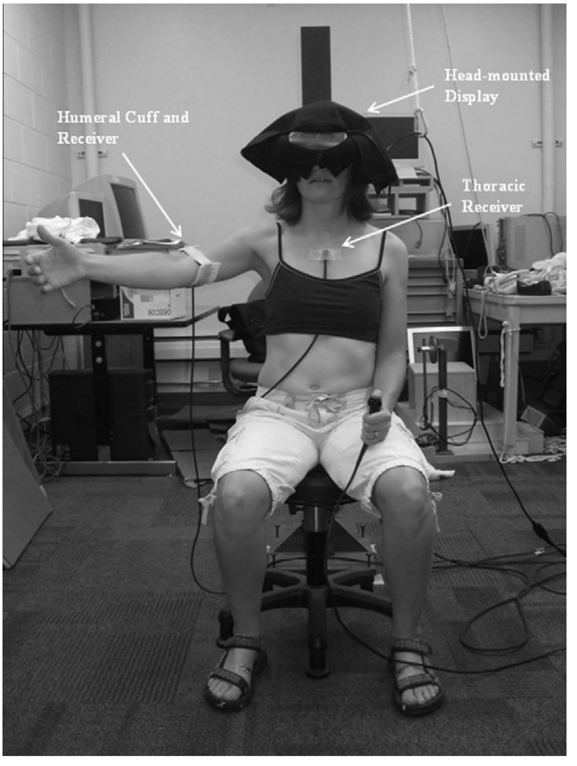

Fig. 1. Photograph of experimental set-up, showing receivers and head-mounted display.

2.4. Testing 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 jewelry that may have contributed to tactile cues during testing. Subjects were seated on a fully adjustable pneumatic stool having no back support in order to minimize cutaneous tactile cues from the lower back. The stool height was adjusted such that their knees were flexed to approximately 90° with their feet flat on the floor (Fig. 1).

Following instrumentation with the sensors and digitization of bony landmarks, maximum shoulder active ROM in horizontal abduction was determined. Subjects were asked to sit on the stool facing forward with the torso erect. While maintaining this trunk and head position, subjects elevated the humerus to 90° in the sagittal plane with respect to the thorax, as confirmed with a realtime display of plane and elevation angles via custom-written LabView software (National Instruments, Austin, TX). While maintaining this elevation angle, subjects were instructed to horizontally abduct the glenohumeral joint to the perceived end range, at which point a trigger was pressed to enter the current glenohumeral plane angle for calculation of target positions to be used during testing. Using this end range angle, the positions used for testing were calculated. First, the range of motion to be covered for testing was calculated as the difference between a position 80° anterior to the frontal plane and 90% of the collected end range angle (Janwantanakul et al., 2001). Then, four angles were calculated that were evenly spaced over this range of motion. Therefore, each subject was tested at angles of 80°, and 22.5%, 45%, 67.5%, and 90% of the calculated horizontal abduction ROM.

The testing protocol was thoroughly explained to the subject while watching the visual output, first on the computer monitor, then through the head-mounted display. A gray screen with a black square in the center was presented to the subject, via custom written LabView software. The black square represented 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 (Fig. 2A).

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 (Fig. 2B). 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 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 so for the remainder of the trial. Subjects were instructed to maintain their shoulder in the target position for a period of five seconds, during which time they were to concentrate only on the position of the shoulder. After the subject had maintained the target position for five seconds, a computer generated voice instructed subjects to "relax", at which time the subject lowered the arm back 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

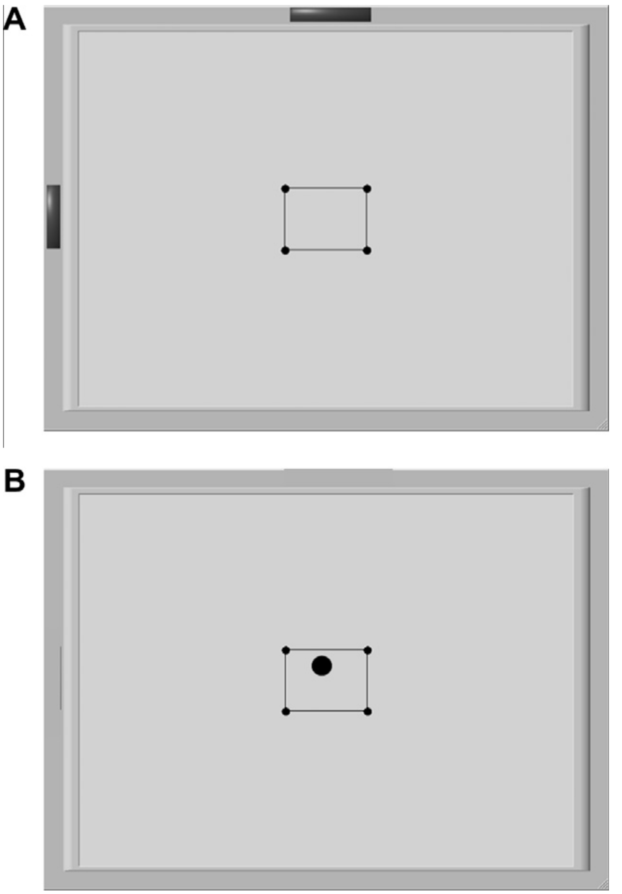

Fig. 2. Computer output seen through the head-mounted display (A) guiding the subject to the target position and (B) with the shoulder in the target position.

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 time-stamp 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.

In practice, to reach the target with visual guidance, the direction provided by the head-mounted display resulted in subjects following a path that would be comprised, for example, of going up, then to the right, then up, then to the left, and so on, until they reached the target. When subjects were attempting to replicate the position, however, they would not follow the same movement trajectory that brought them to the position the first time. Instead, the vast majority would take a more direct route, characterized by an initial relatively fast movement until they got close to the perceived location of the target position, followed by smaller, more refined, corrective adjustments.

During all trials, subjects were instructed to keep their backs straight and face forward, and 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. The procedure was explained and demonstrated to subjects, first while viewing the visual output on the computer screen, and then through the head-mounted display until subjects felt comfortable with the process. Prior to the start of testing, subjects performed several practice trials (at least five) at a target position consisting of a plane of 45° anterior to the coronal plane, and 45° of elevation. The practice trials were repeated until subjects felt comfortable and confident in performing the task. These practice trials may have helped to diminish the conflict between visual cues provided through the head-mounted display and proprioceptive information.

In order to address the effects of shoulder position in the horizontal plane on unconstrained JPS, nine target positions were presented. These positions included the plane angles 80°, and 22.5%, 45%, 67.5%, and 90% of horizontal abduction ROM, all at 90° elevation. Eighty degrees was chosen to be the angle most anterior to the frontal plane so that the location of the visual target represented in the head-mounted display never corresponded to the actual location of the hand with the shoulder in the target position (with the elbow straight). In addition, four distracter positions consisting of 30°, 50°, 70°, and 110° elevation in the scapular plane (35° anterior to the coronal plane) were used to prevent subjects from cueing on the same elevation angle in all trials. These nine trials were automated via 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). Subjects completed three sequences of these nine trials, separated by five minutes.

2.5. Data reduction

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 these plane and elevation angles, as 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 presented and reproduced position vectors was calculated for each trial and taken to represent the absolute magnitude of the repositioning error, absolute error (AE). The AE from each presented position was averaged across the three trial sequences, and the mean was used for further analysis. In addition, variable error (VE) was calculated to determine the consistency of subject performance according to the equation below:

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

where x_i is the AE for an individual trial and X is the AE averaged over the three trial sequences.

2.6. Statistical analysis

PASW, version 17.0 (Chicago, IL), was used for statistical analysis. Two one-way repeated measures analyses of variance (ANOVA) were conducted to determine the effect of shoulder position on absolute and variable errors. In the case of a significant main effect, post hoc analyses with a Bonferroni

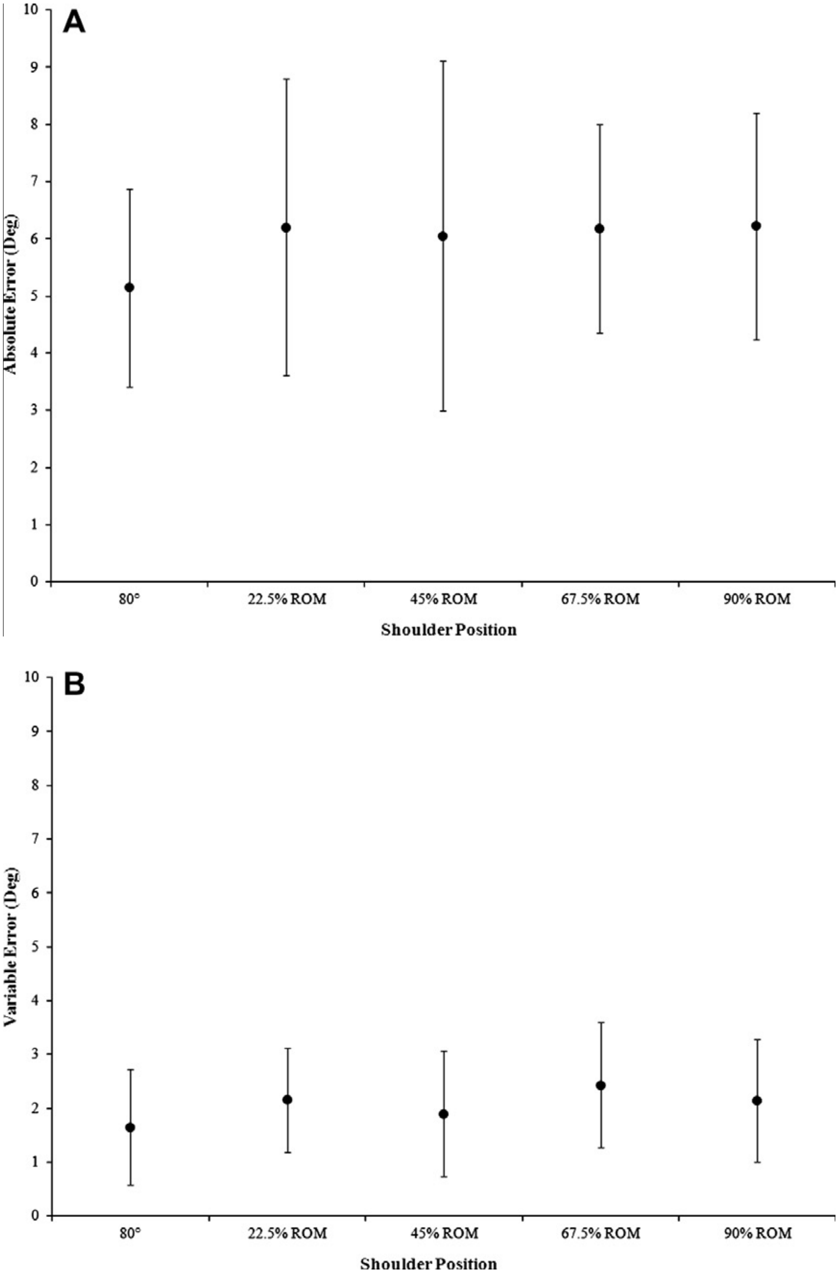

Fig. 3. Effect of altering the target position, with respect to the shoulder angle in the horizontal plane, on (A) absolute and (B) variable repositioning errors at a constant elevation angle (±*SD*).

correction were conducted. An a priori alpha level of .05 was set for the analysis. The size of the effect of position on both absolute and variable errors was expressed as η^2, and calculated as the quotient of the sum of squares associated with the treatment divided by the total sum of squares corresponding to the individual dependent variables. A power analysis was conducted using pilot data, with a minimal detectable difference in error between positions of 2°, a standard deviation of 2.5°, and an α level of .05, revealing that only 14 subjects were necessary to achieve a power level of .8.

3. Results

Mean shoulder horizontal abduction end range measured at 90° elevation for all subjects was −11.30 ± 7.38°. Accordingly, the mean target positions tested to evaluate the effect of shoulder position in the horizontal plane on JPS consisted of 80°, 60 ± 1.7°, 39 ± 3.34°, 18 ± 5.03°, and −2 ± 6.59°. AE across positions ranged from 5.14° to 6.21° at 80° and 90% of end range, respectively (Fig. 3A). VE ranged from 1.6° to 2.4° across positions (Fig. 3B). The results of Mauchley's test indicated that the data for both AE and VE violated the assumption of sphericity, so the Greenhouse-Geisser correction for degrees of freedom was used for statistical analysis of both independent variables. The ANOVA revealed no main effect of position on either AE ($F(3.68, 80.96) = 1.21$, $p = .312$), or VE ($F(2.67, 61.29) = 1.68$, $p = .185$) (Fig. 3). The effect sizes for both AE and VE were small. For AE, $\eta^2 = .052$, while for VE, $\eta^2 = .068$.

4. Discussion

The purpose of the present study was to examine the effect of altering the shoulder position in the horizontal plane on JPS at a constant elevation of 90°. Based on previous data using a similar protocol (Suprak et al., 2006), and based on the fact that elevation angle (and thus, external torque and muscle activation levels) was held constant across target angles, alterations in shoulder position were not hypothesized to affect JPS acuity or variability. This hypothesis was supported, as no effect of plane on either AE or VE was observed. This result is in contrast to the results of several studies employing methods involving internal and external shoulder rotation in 90° of abduction.

Rotational studies of joint position sense have reported enhanced repositioning accuracy in both active (Rogol et al., 1998) and passive (Janwantanakul et al., 2001; Rogol et al., 1998; Safran, Borsa, Lephart, Fu, & Warner, 2001) repositioning of a passively presented position as the presented position approaches the end ROM. In addition, in studies of shoulder kinesthesia, most commonly tested using the threshold to detection of passive motion (TTDPM) method, decreased threshold to detection was found as the starting position approached end range (Allegrucci, Whitney, Lephart, Irrgang, & Fu, 1995; Safran et al., 2001). In TTDPM testing, blindfolded subjects begin with their shoulder abducted to 90° and positioned in some internal/external rotation starting position, and then are asked to indicate when they sense a passive rotational displacement at the shoulder. The TTDPM is measured as the displacement occurring between the onset of the passive movement and the subjects depressing a hand-held trigger.

The disparities in the results of the present and other studies may have arisen from differences in data collection procedures. JPS testing in shoulder rotational movements has classically been performed at slow controlled passive velocities (usually 2.5–10°/s), either during the presentation of the joint position, or during both the position presentation and replication. This method has been reportedly chosen in an attempt to limit the contribution of the muscle spindles to the afferent signal of joint position. Enhanced JPS at end range in these studies may appear to provide support for, at least, an additive effect of combining the afferent signals of musculotendinous and capsuloligamentous receptors, since JPS improves in positions where both are active. In the current study, no attempt was made to limit muscle spindle contribution by controlling and limiting the speed of movement, although the approximate movement velocity was demonstrated, and subjects were instructed to make smooth movements. In fact, the contribution of muscle spindles to JPS in the present protocol may have been enhanced due to the subject requirement to actively achieve, maintain, and replicate the target position unsupported against gravity. Since no enhancement of JPS was observed at end range in this study, our results do not support an additive effect of capsuloligamentous and musculotendinous afferent signals in unconstrained movements.

Although the present study differed from previous studies in that subjects were required to support the mass of the arm against gravity, the shoulder angle as the target position approached end ROM was similar to that in previous rotational studies. In previous studies, numerous authors have employed a 90° abducted position of the shoulder for testing, with movement restricted to shoulder internal and external rotation (Allegrucci et al., 1995; Janwantanakul et al., 2001; Rogol et al., 1998). Janwantanakul et al. (2001) used similar percentages of ROM for the testing positions (50%, 75%, and 90%) to those utilized here. In the 90% ROM position in the present study, the shoulder was in a position similar to that seen in the 90% position in the Janwantanakul study, since subjects in the present study were instructed to perform all movements with the thumb side of the hand pointed upward (resulting in approximately 90° external rotation, as compared to the average 80° of external rotation reported by Janwantanakul in the 90% position). Thus, the shoulder capsule and glenohumeral ligaments should have been similarly stretched in these positions across the two studies.

In the present study, the shoulder position in the horizontal plane was altered across target positions, while the elevation angle was held constant. Therefore, in all presented positions analyzed, the external torque at the shoulder, and theoretically, the activation levels of muscles supporting the arm against gravity were relatively unchanged in each target position. Due to a mechanism known as α-γ coactivation, muscle spindle sensitivity to length changes appears to be influenced by the level of extrafusal muscle activation (Durbaba et al., 2003; Jami, Lan-Couton, & Petit, 1980). Although muscle spindle stretch sensitivity is known to be dependent on intrafusal muscle contraction history, a characteristic known as thixotropy, this contraction history-dependence appears to become progressively less as the level of muscle activity increases (Winter, Allen, & Proske, 2005), and would not have been appreciably different across the positions tested in this study. This contention is supported by previous results from our group indicating that JPS is enhanced in positions of increased torque (Suprak et al., 2006) and under conditions of increased load at the same position (Suprak et al., 2007).

In addition to the afferent signals arising from mechanoreceptors in the periphery, several authors have suggested a role of the motor command in the appreciation of joint position, although the nature of this role remains to be determined (Allen et al., 2007; Gandevia et al., 2006; Smith et al., 2009; Walsh et al., 2010). This signal has been hypothesized by some authors to be integrated with the signal from muscle spindles, with fusimotor activation driving a forward model in which it is compared to previous experiences to derive the expected spindle signals from the movement performed (Matthews, 1988). Other authors, however, have provided evidence that the motor command may signal position directly (Smith et al., 2009). In the current investigation, the magnitude of the motor command should have been quite similar across positions at a constant elevation angle. In passive testing paradigms (Janwantanakul et al., 2001; Rogol et al., 1998; Safran et al., 2001), there is no motor command, although muscle spindle discharge will vary with position, due to muscle length changes. These paradigms have consistently resulted in enhanced JPS at end ROM. However, when both the motor command and muscle spindle output are similar across joint positions, as in the present study, JPS is unaltered. Although the role of the motor command may be enhanced with increased effort when gamma activation may render muscle spindle signals ambiguous (Gandevia et al., 2006), afferent signals appear to be important adjuncts in order to create an accurate sense of joint position, since when the afferent signals are occluded via temporary anaesthesia, the illusion of joint movement has been reported by subjects to be associated with the magnitude of attempted muscle activation (Walsh et al., 2010).

Although capsuloligamentous receptor activation is enhanced at end ROM (Salo & Tatton, 1993; Steinbeck et al., 2003; Vangsness et al., 1995), the non-significant effect of shoulder position in the present study may indicate that the relatively unchanged muscle spindle sensitivity to joint position, along with the relatively constant motor command signal, are weighted more heavily by the CNS in constructing the overall representation of the state of the limb during unsupported movements against gravity. Given the fact that, even in active movements, capsuloligamentous stretch is passive, the combination of signals from the muscle spindle and motor command may provide a more reliable indicator of joint position, movement, and perturbation.

In a previous study using a protocol similar to that used in this study, JPS acuity was unaffected by changes in external shoulder joint torque (imposed by either an upright or 45° tilted position) at the same elevation angle, while JPS was affected by changes in joint position at the same external joint torque (Chapman, Suprak, & Karduna, 2009). When subjects in that study moved the shoulder to the elevation angle matching a given external shoulder torque in the upright position, the motor command employed to get there was theoretically of greater magnitude than that needed to arrive at the position matching the same external torque in the tilted position (i.e., 90° in upright, 45° in tilted position). However, the muscle spindle discharge at the given positions of identical torque would theoretically be the same. These authors reported consistently greater JPS acuity in the upright position. This greater JPS acuity in the upright position may have in part been the result of a greater role of the motor command in interpreting the same afferent spindle signal, or the greater context of previous movement experiences available to the CNS in the upright posture, leading to more accurate JPS. This result may be an illustration of the importance of the motor command to provide a context in which to interpret muscle spindle discharge. This effect should be explored further in the future.

The repositioning errors observed in the present study are comparable to those previously reported in the literature employing similar protocols. In rotational studies exploring JPS in the shoulder and knee, absolute errors ranged from 2° to 8° (Bullock-Saxton, Wong, & Hogan, 2001; Janwantanakul et al., 2001; Lephart, Warner, Borsa, & Fu, 1994; Skinner, Wyatt, Hodgdon, Conard, & Barrack, 1986; Voight et al., 1996), while in more unconstrained protocols examining shoulder JPS, they ranged from 3° to 9° (Suprak et al., 2006, 2007; Tripp, Boswell, Gansneder, & Shultz, 2004; Yang, Chen, Jan, Lin, & Lin, 2008). Absolute errors in the present study across shoulder positions ranged from 5.1° to 6.2°. Variable errors in previous similar investigations of shoulder JPS have ranged from 2° to 7° (Janwantanakul et al., 2001; Tripp, Yochem, & Uhl, 2007; Tripp et al., 2004). The variable errors observed in the present study, ranging from 1.6° to 2.4°, are on the lower end of this range, but compare well to the literature.

In contrast to previous studies employing uniaxial rotations in a supported abducted position, the current results indicate that shoulder JPS is not enhanced at end ROM in an unconstrained repositioning task. Therefore, these results may support the combination of the motor command, α-γ coactivation, and muscle spindle afferent signals as a dominant source of information used by the CNS to construct the internal representation of joint position in unconstrained movements. Taken together with the results of our previous studies (Suprak et al., 2006, 2007), these findings may indicate that shoulder JPS is most accurate under increased external torque, regardless of the proximity to end ROM. Therefore, strengthening and rehabilitation exercises performed in multiple positions under conditions of increased muscle activation may help to enhance shoulder joint stability and avoid injury.

4.1. Conclusion

The findings of this study add to what is known about the behavior of shoulder JPS as the joint approaches end range and expands that knowledge to include unconstrained tasks, which may better apply to functional movements. In addition, these findings may further indicate a preferential weighting of information arising from the muscle spindles and the motor command over the capsuloligamentous receptor signal in allowing the central nervous system to generate an internal representation of the state of the limb.

Shoulder JPS appears to be enhanced as the external torque on the joint increases, regardless of the proximity to the end range of motion. Thus, strengthening and rehabilitation exercises performed in multiple positions under conditions of increased muscle activation may help to enhance shoulder joint stability and avoid injury.

There is much still to be learned regarding the coordination of the motor command, α-γ coactivation, and afferent signals from the joint and muscle spindles in deriving the sense of joint position. Therefore, future research should be aimed at further elucidating the contribution of the motor command and how it is used in relation to the afferent signals to construct the internal model of joint position and movement and make decisions on subsequent movements.

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