Shoulder Joint Position Sense Improves with Elevation Angle in a Novel, Unconstrained Task

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Received 15 June 2005; accepted 3 October 2005

Published online 6 February 2006 in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/jor.20095

ABSTRACT: Proprioception, encompassing the submodalities of kinesthesia and joint position sense, is important in the maintenance of joint stability, especially in the shoulder. The purpose of this study was to examine the effects of plane and elevation angle on unconstrained shoulder joint position sense. Twenty-two subjects (12 male, 10 female) without a history of shoulder pathology were recruited from a university campus. Subjects attempted to replicate, with respect to plane and elevation angles, various target positions. Target positions consisted of five plane angles at 90° of arm elevation and five arm elevation angles in the scapular plane. All target positions were tested twice to assess the reliability of the measurement. Intraclass correlation coefficients were generally low across target positions, possibly owing to the novelty and demanding nature of the task. No differences in repositioning errors were observed between plane angles ($p = 0.255$). Repositioning errors decreased linearly as the elevation angle increased from 30° to 90° ($p = 0.007$) and increased again from 90° to 110° of elevation ($p = 0.029$). Our results suggest that unconstrained joint position sense may be enhanced with increased muscular activation levels. Further, afferent feedback from musculotendinous mechanoreceptors may dominate over that from capsuloligamentous sources in unconstrained movements. © 2006 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 24:559–568, 2006

Keywords: proprioception; joint position sense; muscle activation; shoulder

INTRODUCTION

Joint stability is important for coordinated performance of functional tasks of daily living as well as for more demanding athletic skills. Stability is afforded via factors such as the degree of bony congruity, integrity of capsuloligamentous supporting structures, and feedback loops involving joint and musculotendinous mechanoreceptors that are integrated with the central nervous system. The effects of these feedback loops have collectively been termed *proprioception*, as defined by Sherrington in 1906.[1] Since that time, proprioception has been compartmentalized into submodalities and has recently been described as a combination of joint position sense, the ability of a person to identify the position of a limb in space, and kinesthesia, the ability to detect limb movement.[2]

The role of proprioceptive mechanisms in the maintenance of joint stability is especially important for the shoulder, as compared to other synovial joints, where stability is sacrificed for a large range of motion (ROM).[3] This relative shoulder instability is due to low bony congruity and relative inefficiency of mechanical restraints provided by the joint capsule and ligaments in dynamic conditions.[4] It has been postulated that afferent signals arising from shoulder musculotendinous and capsuloligamentous mechanoreceptors enable the central nervous system to maintain muscle stiffness and coordination about the joint and produce smooth movements while minimizing the chance for joint injury.[5]

Joint position sense is commonly tested using either active or passive reproduction of joint positioning. In these paradigms, the shoulder joint

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of a blindfolded subject is moved through a range of rotation via a mechanical device to a predetermined target position and held for a period of time (usually 5–10 s). Upon returning to the starting position, subjects attempt to replicate the target position, either by means of active movement or by passive movement induced by the mechanical device during which subjects indicate when they feel the presented position has been matched. The difference between the presented and reproduced position is recorded as the repositioning error. Movements in passive positioning conditions are most commonly performed at speeds of 0.5 to 2°/s.[6–9] However, functional activities are performed predominately in the presence of active muscle contraction. Further, the speeds chosen for testing in the passive paradigms are much slower than those seen in functional tasks. For these reasons, active joint position sense testing methods are hypothesized to better indicate joint function than passive protocols.[8] Joint position sense is thought to be provided by the slowly adapting musculotendinous (muscle spindles, golgi tendon organs) and capsuloligamentous (Ruffini, and golgi tendon organlike endings) mechanoreceptors.[3]

Capsuloligamentous mechanoreceptors are stimulated upon deformation of their parent tissue.[10,11] Several authors have hypothesized that these receptors are stimulated more in the end ranges of motion, compared to the mid ranges, due to the elongation of their parent tissues in these ranges.[12–14] In the shoulder, this hypothesis has been supported by several studies examining joint position sense in one plane, which have reported enhanced position sense as the presented angle approaches end range.[3,15,16] To our knowledge, however, this effect has not been studied in an unconstrained model.

Although the capsuloligamentous receptors are relatively inactive in the midranges of motion, when the tissues are slack, afferent information regarding joint position is still relayed to the central nervous system from the periphery. Therefore, musculotendinous mechanoreceptors have been hypothesized as the primary contributor to joint position sense in the mid ranges of motion. This hypothesis is supported by the pronounced detrimental effect that muscle fatigue exerts on joint position sense, both in active and passive reproduction paradigms.[8,17] These mechanoreceptors are more highly stimulated in the presence of and following muscular contraction and tension, with more intense activation being associated with more intense contractions.[18,19] However, the extent to which muscle activation level affects joint position sense has not yet been explored.

Several studies examined upper extremity proprioception in an unconstrained model.[20,21,38] However, to date, no study has examined shoulder joint position sense in multiple planes, using a testing paradigm employing active reproduction of active positioning. Therefore, the purpose of this study was twofold: to examine the effect of plane angle on repositioning error at a constant elevation, and to examine the effect of arm elevation angle on repositioning error in the scapular plane, in an unconstrained testing paradigm. We hypothesized that as the shoulder joint angle approached the end range plane angle, position sense would be enhanced, due to stretching of the capsuloligamentous structures. As the presented elevation angle increased toward 90°, we further hypothesized that muscle activation, and therefore muscle spindle and golgi tendon organ activation, would increase due to the increased torque about the joint in that position. We expected that this increase in muscle spindle and golgi tendon organ activation would be manifested in decreased repositioning error.

MATERIALS AND METHODS

Twenty-two healthy individuals (12 males, 10 females) with a mean age of 23.7 years (± 4.8), a mean height of 172.9 cm (± 10.1), and a mean body mass of 72.4 kg (± 14.3) agreed to participate in the study. Prior to participation, all subjects signed an informed consent form approved by the university's Institutional Review Board (IRB). Subjects were included in the study only if they had no history of shoulder pathology requiring surgery or physical therapy. Exclusion criteria included limited ROM in arm elevation and previous diagnosis of shoulder instability or other pathology that might alter neuromuscular control of the shoulder. However, no direct measurements of either shoulder or generalized joint laxity were made. In addition, no individuals involved in competitive or recreational overhand throwing activities were included.

Instrumentation

Kinematic data were collected using the Polhemus Fastrak 3Space magnetic tracking system (Colchester, VT). The Polhemus unit consists of a transmitter, three receivers, and a digitizer. The transmitter emits an electromagnetic field that is sensed by the receivers and digitizer. Signal strength and orientation are used to determine relative position and orientation of the receivers in space. To track movement of the humerus with respect to the thorax, receivers were placed on the sternum, approximately 1.5 cm inferior to the jugular notch,[22] and on the humerus just above the lateral epicondyle, via a custom-molded Orthoplast^{TM} cuff and Velcro^{TM} strap. In addition, one receiver was fastened to the acromion process[23] for digitization purposes, but was removed prior to testing. The transmitter was positioned level to the thoracic receiver with the subject seated.

Following attachment of the receivers, various bony landmarks were digitized on the thorax and humerus to establish anatomical coordinate systems, in accordance with the standard endorsed by the International Society of Biomechanics.[24] The body segments and corresponding digitization points were: thorax—C7, T8, jugular notch, and xiphoid process (Fig. 1a); humerus—medial and lateral epicondyles and humeral head (Fig. 1b). 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.[25] 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.[26] According to our established anatomical coordinate systems, this Euler sequence corresponded to a z-x′-z″ rotation sequence.

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 could view the computer output with complete visual occlusion of the position and movement of the shoulder joint.

Testing Procedures

All testing was completed in a single session and performed on the dominant upper extremity. Subjects performed a standardized warm-up procedure including Codman's pendulums and stretches for the rotator cuff muscles. Codman's pendulum exercises were performed with subjects bent over with the nondominant hand on a table, and holding a 2.5 lb (11.1 N) weight in their dominant hand with the weight hanging down at arm's length. Subjects performed 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.[27] Stretches consisted of holding a static external and then internal rotation position, both with the shoulder abducted to approximately 90°, for two sets of 15 s each. 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

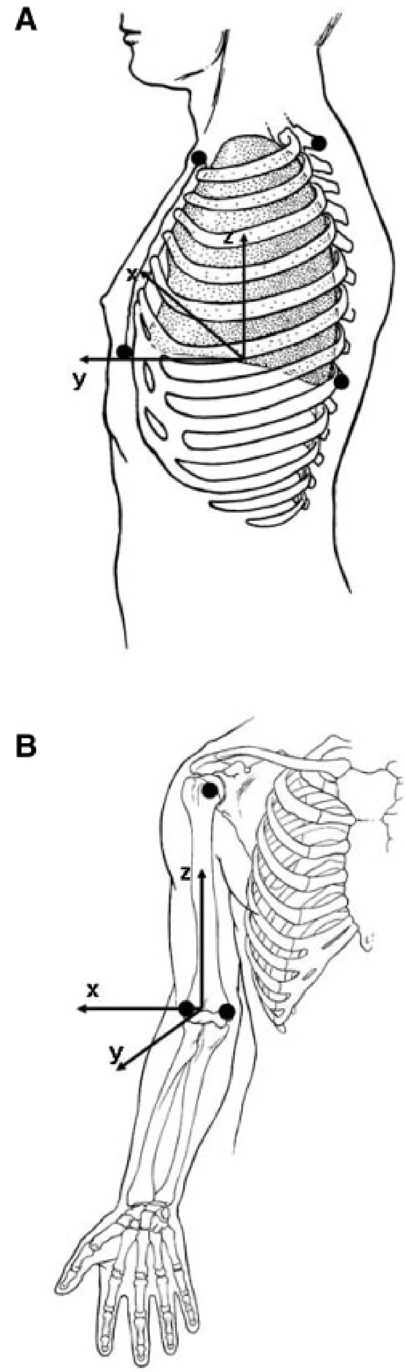

Figure 1. Depiction of digitized points and anatomical coordinate systems for the (a) thorax and (b) humerus.

without back support 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. 2).

The testing protocol was thoroughly explained to the subject while watching the visual output, first on the

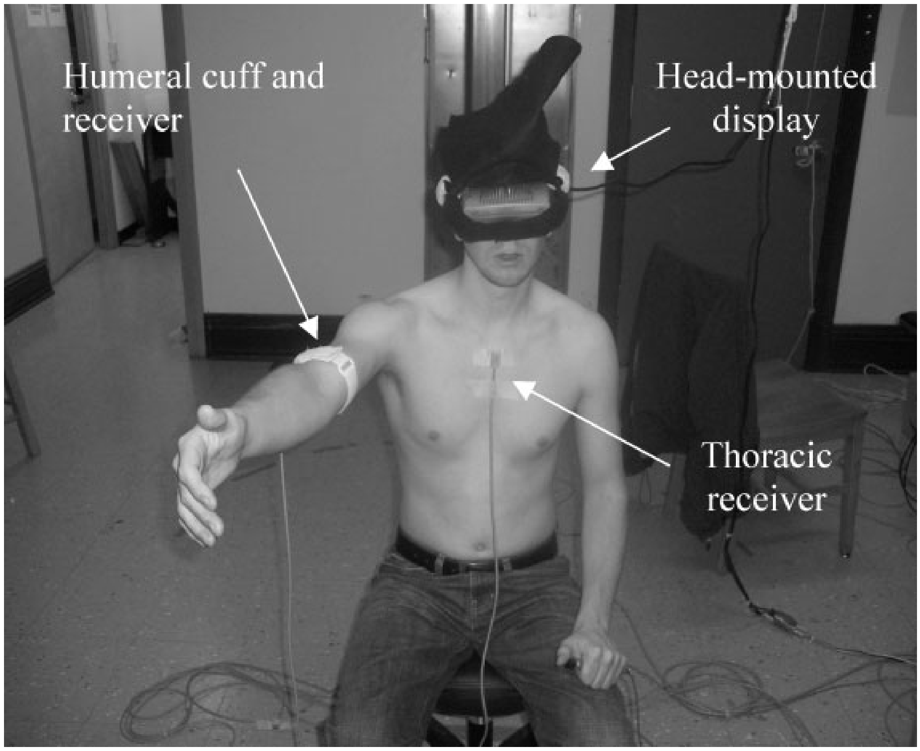

Figure 2. Photograph of experimental set-up showing sensors and head-mounted display.

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 (National Instruments, Austin, TX). The black square represented the target position for a given trial. On the four sides of the screen, rectangular boxes appeared to prompt subjects as to which direction to move their arm to arrive at the target position (Fig. 3a).

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 5° 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. 3b). 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. Once the shoulder was in the target position for 1 s, 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 5 s, during which time they were to concentrate only on the position of the shoulder. After the subject maintained the target position for 5 s, a computer-generated voice instructed subjects to relax, at which time the subject lowered the arm back to the side.

Three seconds later, another computer generated voice instructed subjects to return. Subjects then attempted to replicate the 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 to time-stamp the reproduced position. Subjects were instructed to maintain the shoulder in the reproduced position for 1 s after pushing the trigger button, at which time an audible beep sounded and the trial ended.

The procedure was explained and demonstrated to subjects until they felt comfortable with the process. Prior to the start of testing, subjects performed at least five practice trials 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. To address effects of plane and elevation on unconstrained joint position sense, nine target positions were presented: elevation angles of 30°, 50°, 70°, 90°, and 110° in the scapular plane (defined as 35° anterior to the coronal plane) and plane angles of 0°, 20°, 35°, 60°, and 80° at 90° of elevation. These nine trials were automated via the software, and separated by a 15-s rest interval. The target positions were presented in random order, according to a balanced Latin square design.[28] To establish reliability, the nine trials were repeated in a

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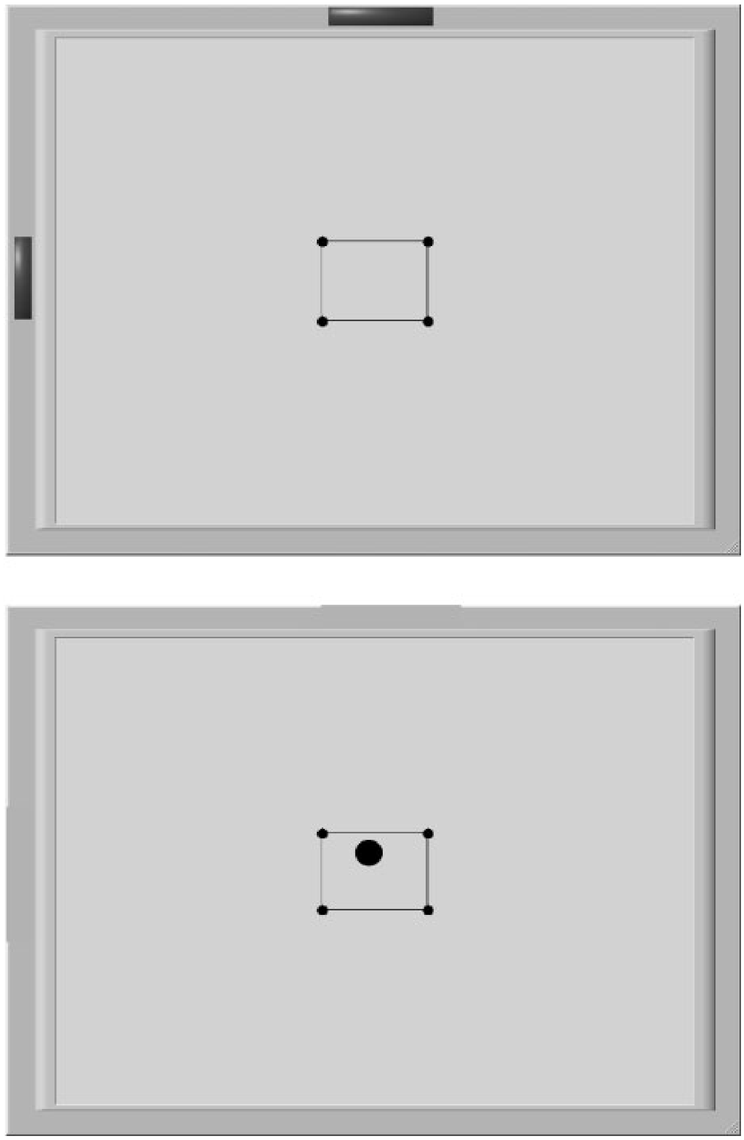

Figure 3. Computer output seen through the head-mounted display (A) guiding the subject to target position and (B) with the shoulder in the target position.

randomized order unlike that used for the first nine-trial sequence, following a 10-min rest period. Thus, subjects completed a total of 18 trials (two trials at each of the nine positions).

Kinematic data were converted into humeral plane and elevation angles, using transformation matrices between the thoracic and humeral coordinate systems. 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 assumed to represent the absolute magnitude of the repositioning error (Fig. 4)

Statistical Analysis

SPSS version 13.0 (Chicago, IL) was used for statistical analysis. Intraclass correlation coefficients [ICC (3,1)][2,29] and standard errors of measurement values were calculated for repositioning error magnitude at each target position using the observed errors from before and after the 10-min rest interval. Two repeated measures analyses of variance (ANOVA) were conducted to determine the effect of plane and elevation angles on the magnitude of repositioning error. For analysis of the effect of plane on repositioning error, the five target positions consisting of various plane angles at 90° of elevation were included. For analysis of the effect of elevation angle,

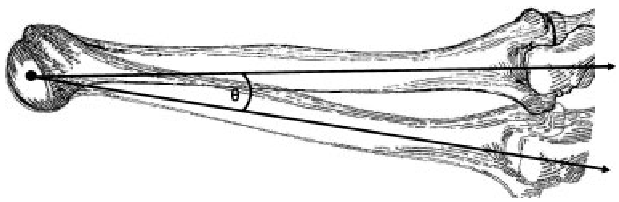

Figure 4. Depiction of repositioning error calculation.

the five target positions consisting of various elevation angles in the scapular plane were included. If a main effect was found for plane or elevation angle, polynomial contrasts were conducted to uncover significant linear trends. An a priori α level of 0.05 was set for all analyses.

RESULTS

ICCs for repositioning error magnitude were variable at different presented shoulder positions, and most were found to be relatively low (between −0.11–0.69; Table 1). For statistical analysis, the error scores for each position from the two test sequences were averaged together, and the mean errors were used in all further analyses.

The ANOVA revealed no main effect for plane angle on repositioning error magnitude [$F(4, 18) = 1.36$, $p = 0.255$, Fig. 5a]. However, the ANOVA for elevation angle revealed a main effect on repositioning error [$F(4, 18) = 6.431$, $p < 0.001$]. A significant linear decrease ($p = 0.002$) in repositioning error was observed with increasing elevation angle, with the smallest error observed at 90°. A sharp increase in repositioning error occurred from 90° to 110° of elevation. Because torque about the shoulder theoretically peaks at 90° of elevation, the data were divided into positions at or below 90° elevation and positions at or above 90°. The linear contrast was repeated excluding the data for 110° of elevation, revealing a more pronounced linear decrease ($p < 0.001$) in repositioning error as shoulder elevation increased to 90° (Fig. 5b). A pairwise comparison revealed a significant increase in error from 90° to 110° of elevation ($p = 0.029$).

Table 1. ICC and Standard Error of Measurement Values for Repositioning Errors/Across Presented Positions

Joint Position (Plane/Elevation, Deg)	ICC	SEM (Deg)
35/30	0.36	3.99
35/50	0.69	3.03
35/70	0.26	3.51
35/90	0.49	1.90
35/110	0.23	3.18
0/90	−0.11	3.72
20/90	0.10	4.07
60/90	0.45	2.55
80/90	0.43	2.39

DISCUSSION

The purpose of the present study was to determine the effects of plane and elevation angles on repositioning error in an unconstrained joint position sense testing paradigm. In examining the effect of plane, we hypothesized that, due to stretching of the capsule and ligaments as the plane angle approached 0° (coronal plane), repositioning error would decrease. However, this hypothesis was not supported, as no effect of plane on repositioning error was observed. Often when a nonsignificant effect is observed, the power of the analysis becomes an issue. A power analysis conducted using pilot data, with a minimal detectable difference in error between positions of 2°, a standard deviation of 2.48°, and an α level of 0.05 revealed that only 12 subjects were necessary to achieve a power level of 0.8. 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[16] and passive[3,7,16] 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.[7,29] 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 between the results of these studies and the present findings may have arisen from multiple sources. In our study, the most

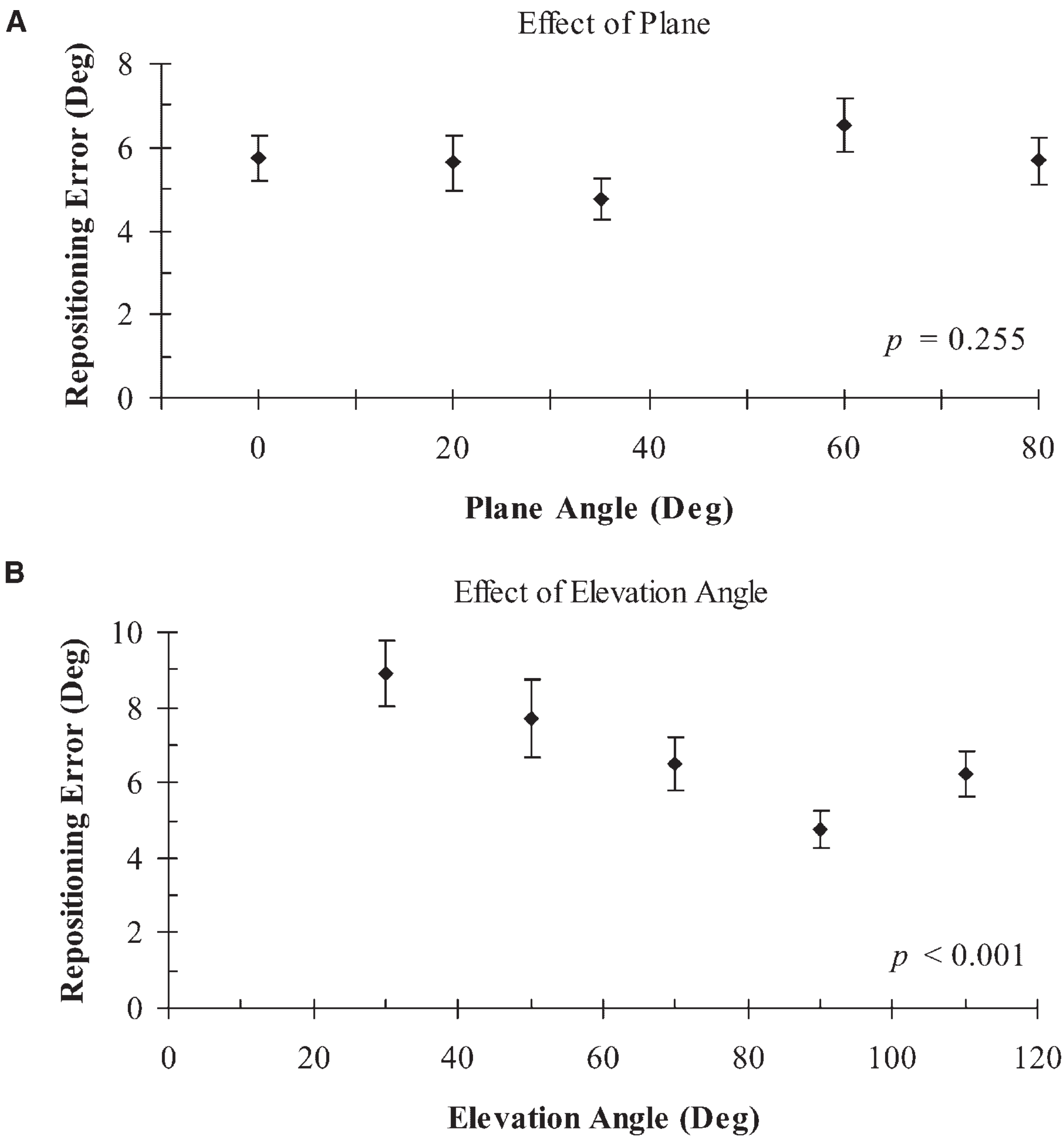

Figure 5. Vector error magnitude across (A) plane and (B) elevation angles.

extreme plane angle (0°) was standardized for all subjects and was not normalized to each subject's ROM. The mean ROM in horizontal abduction for our sample was 30° posterior to the coronal plane. Therefore, subjects may not have sufficiently approached their end range to result in significant stretching of the capsular and ligamentous receptors. Another possible explanation of this result is related to the nature of the measurement. Although the joint position with respect to the plane angle was varied from 0° to 80°, subjects were required to maintain the elevation angle of 90° against gravity in all of these positions. Because afferent input from muscle spindles may be the primary contributor to joint position sense,[8] the information provided by these receptors may have overridden that provided by the capsuloligamentous receptors, leading to a nonsignificant effect of plane. In previous uniplanar studies reporting enhanced joint position sense near the end ROM, the arm was supported by the testing apparatus,[3,7,16] whereas in our study, position was maintained by active muscle contraction.

Our results indicate that joint position sense is affected by elevation angle, as illustrated by the significant linear decrease in repositioning error from 30° to 90° of elevation and the subsequent increase in error as elevation further increased to 110°. As the shoulder elevation angle increases, the torque applied to the shoulder due to gravity increases with the increasing moment arm of the center of mass of the upper extremity, theoretically peaking at 90° of elevation. Therefore, the muscular effort required and tendon tension developed in both attaining and remaining in the target position for the 5-s period, and then returning to that position, presumably increased as the elevation angle approached 90°. We hypothesize that, if positions higher than 110° elevation were tested, the repositioning error would further increase as the torque decreased. However, 110° was the highest elevation angle tested in this study.

The γ motor neurons innervating intrafusal muscle fibers are activated simultaneously with α motor neurons innervating extrafusal muscle fibers.[30] This coactivation of both the intrafusal and extrafusal fibers maintains the sensitivity of muscle spindle afferents over the full ROM.[30] Poppele and Quick reported that the sensitivity of muscle spindles in the cat tenuissimus muscle, a hip abductor, is directly related to the degree of muscle contraction.[31] Myers and colleagues examined shoulder internal rotator muscle onset latency in response to an imposed external rotation perturbation at various levels of muscle activation.[5] They found that muscle onset latency was significantly reduced in the presence of some level of muscle activation prior to perturbation. They attributed this effect to a heightened sensitivity of the muscle spindle afferents associated with the involved musculature. This result has been corroborated by various authors examining muscle spindle afferent responses to passive versus active stretching perturbations[32] and to increases in γ motor neuron stimulation.[33,34]

Group Ib golgi tendon organ afferents respond to tension developed within the tendons associated with contracting or stretched muscle fibers.[30] As tension within the tendon increases, Ib afferent stimulation rises.[18] Due to the increased gravitational torque as the elevation angle approached 90° in our study and the presumed increase in required muscular activation level, our results may have been due to heightened musculotendinous mechanoreceptor sensitivity as the presented shoulder position increased in elevation. However, as the elevation angle increases, the changes in muscle length, capsular tightness, and scapular orientation also take place, which may affected the observed findings. Further investigation is needed to examine more directly the effect of muscle activation level on unconstrained joint position sense.

The ICC values calculated for most of the joint positions tested were quite low (Table 1). This may be partly due to the novelty of the task. Studies involving joint position sense testing in internal/external rotation have reported ICC values higher than those reported here.[3,35] However, subjects in our study were asked to find a joint position, to hold the shoulder in this position for 5 s, concentrating only on shoulder position, and to replicate the position in two planes. The observed variability in the error scores from one testing interval to another may have been due to the demanding nature of the protocol, making the measurement more variable within subjects. Visual inspection of the data for all subjects across the two trial sequences revealed a large variation in error scores between testing sequences within subjects. In contrast, the variability of scores between subjects was noticeably smaller, contributing to the low ICC values observed. To account for some of the within-subject variability, the mean of the error scores for each joint position during both testing intervals was used in all statistical analyses. Future studies employing this testing method should include more trials at each joint position to obtain a more representative error score.

The magnitudes of the repositioning errors in our study differ from those previously reported in the literature for uniplanar rotational studies. In rotational studies examining joint position sense at the shoulder and knee, the repositioning errors ranged from 2° to 5°,[8,35–37] whereas in our study, they ranged from 4° to 9°. Therefore, there is some overlap in the errors seen in our study and those employing uniaxial testing methods. The differences may be due to the more challenging nature of our measurement protocol, in that subjects were required to reposition the joint in two planes rather than only one.

In the present study, we found no significant difference between repositioning errors at different plane angles, but JPS did vary with alterations in elevation angle. These results suggest that signals arising from musculotendinous mechanoreceptors are an increasingly important source of afferent feedback contributing to shoulder joint position sense in multiple planes, and that increased muscle activation results in enhanced sense. Active muscle contraction is essential to maintaining shoulder joint stability. Our findings may lend further insight into the important proprioceptive role played by shoulder musculature during dynamic conditions. These findings may also have implications for improving dynamic shoulder stability in the rehabilitation setting, advocating the prescription of exercises utilizing unconstrained movements in functional ranges under conditions and positions of increased muscle activation to optimize proprioceptive feedback from musculotendinous mechanoreceptors. However, further study is required to determine the effects of muscle activation level directly on unconstrained shoulder joint position sense.

Future research should focus on the effect of altering the muscle activation level involved in this type of experimental paradigm at a given target position on the repositioning error observed. The results of such a study would provide more direct evidence of the behavior of musculotendinous receptors in functional situations. This line of research may be further extended to the investigation of how joint position sense is affected by conditions of external loading in patients with shoulder injuries to gain insight into the extent of damage to musculotendinous receptors in such conditions and provide more specific guidelines for rehabilitative efforts in the clinical setting.

ACKNOWLEDGMENTS

The authors would like to thank Brian Fedor for technical assistance.

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