Human Movement Science 67 (2019) 102508

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Quantifying the three-dimensional joint position sense of the shoulder

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ARTICLE INFO

Keywords:
Proprioception
Glenohumeral joint
Joint angle replication

ABSTRACT

Joint position sense is important for performing activities of daily living and recreational activities. The objective of this study was to develop new insights into the proprioceptive capabilities of the shoulder using a novel virtual reality paradigm where participants actively recreated shoulder positions in all three dimensions. This allows for better identification of changes in joint position sense across different shoulder postures. Ten males and ten female healthy adults matched a cursor controlled by shoulder rotations calculated from motion capture tracking, to a target shoulder position presented in a virtual environment with the use of a virtual reality headset. Four elevation angles, three plane of elevation angles, and three rotation angles were investigated, totaling thirty-six angles that encompassed the range of motion of the shoulder. Joint position sense was enhanced as the elevation angle was increased, and further enhanced when the arm was more externally rotated and elevated. As elevation angle increased to 90°, joint position sense significantly increased. There was also a significant interaction of external rotation on elevation angle. As elevation angle increased, participants were more accurate when the arm was externally, but exhibited greater variability. These improvements in joint position sense are likely produced by increased tension in muscles and capsuloligamentous mechanoreceptors within the shoulder. As many sports and activities of daily living require joint position sense to complete a task, the ability to elevate and externally rotate is important for adequate shoulder proprioception and control.

1. Introduction

Proprioception is the ability of the central nervous system to process sensory feedback to accurately know the position and orientation of its limbs relative to the body itself. The central nervous system receives its overall sense of the position, movement and acceleration of body segments using afferent feedback from capsuloligamentous, musculotendinous and tactile mechanoreceptors (Riemann & Lephart, 2002). Proprioception can be experimentally assessed by measuring an individual's joint position sense, or the ability to accurately replicate the position and orientation of its limbs without visual or vestibular information (Aydin, Yildiz, Yanmis, Yildiz, & Kalyon, 2001). During examinations of joint position sense, participants are often blindfolded while the joint is moved passively or actively to a specific posture and then participants are asked to reproduce the prescribed position after a brief break. These evaluations can be performed on upper or lower extremity joints, and are often performed in clinical settings (Goble, 2016). Assessments of proprioception are important clinically, as proprioceptive deficits may contribute to instability and injury of the joint

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https://doi.org/10.1016/j.humov.2019.102508
Received 7 September 2018; Received in revised form 30 July 2019; Accepted 30 July 2019
Available online 12 August 2019
0167-9457/

(Lephart, Warner, Borsa, & Fu, 1994). For a postoperative athlete to return to functional activity, rehabilitation exercises incorporating joint position sense are important to regain dynamic neuromuscular control of the shoulder (Lephart, Pincivero, Giraido, & Fu, 1997).

In particular, shoulder joint position sense is incredibly important for performing activities of daily living and recreational activities given the vast mobility of the shoulder. There is often a need to move the upper extremity to achieve postures outside an individual's vision. For example, proprioceptive feedback during the wind-up phase of an overhand throw can influence the velocity and trajectory of the upcoming throw. Proprioceptive deficits in pitchers can alter muscle activity at the shoulder and exacerbate rotator cuff loading (Safran, Borsa, Lephart, Fu, & Warner, 2001). Mechanoreceptors in the muscles, joints and tendons are activated by changes in tension leading to differences in proprioception across various shoulder postures (Janwantanakul, Magarey, Jones, & Dansie, 2001). As the shoulder is moved throughout its range of motion, muscles acting at the shoulder will change in activation, length and tension, leading to increased afferent feedback from capsuloligamentous and musculotendinous mechanoreceptors, and improved joint position sense.

The assessment of shoulder joint position sense is common both in research and the clinic but methods are not currently standardized (Dover & Powers, 2003). It has been studied using simple goniometers and motion capture tracking systems as participants performed passive (Adamovich, Berkinblit, Fookson, & Poizner, 1998; Anderson & Wee, 2011; Blasier, Carpenter, & Huston, 1994; Hung & Darling, 2012; Janwantanakul et al., 2001) or active positioning (Barden, Balyk, Raso, Moreau, & Bagnall, 2004; Chapman, Suprak, & Karduna, 2009; King & Karduna, 2014; Suprak et al., 2006, 2007; Zanca, Mattiello, & Karduna, 2015), along with constrained (Carpenter, Blasier, & Pellizzon, 1998; Lee, Liau, Cheng, Tan, & Shih, 2003; Lephart et al., 1994; Rogol, Ernst, & Perrin, 1998; Safran et al., 2001) or unconstrained (Chapman et al., 2009; King & Karduna, 2014; Suprak et al., 2006, 2007; Suprak, 2011; Zanca et al., 2015) tasks. Clinical studies have further assessed the effects of kinesiotaping (Zanca et al., 2015), muscle fatigue (Zanca, Grüninger, & Mattiello, 2016), overhead athletes (Safran et al., 2001), and rotator cuff injury (Anderson & Wee, 2011) on shoulder joint position sense. Joint position sense is found to improve as the arm is elevated upwards to 90° at the side, and is unaffected by changes in plane of elevation angle (Suprak, Osternig, van Donkelaar, & Karduna, 2006). However, all of these studies have limited the reproduction of shoulder joint positions to one or two dimensions, even though the vast mobility of the shoulder requires individuals to accurately position their shoulder in all three planes of motion (elevation, plane of elevation, and rotation).

Therefore, the objective of the current study was to develop new insights into the proprioceptive capabilities of the shoulder using a novel virtual reality paradigm that allowed participants to actively recreate shoulder positions in all three dimensions. Participants shoulder joint position sense was examined across 36 distinct shoulder postures, encompassing a large workspace of the shoulder joint. We hypothesized that joint position sense would be enhanced as elevation angles approached 90°, in agreement with previous literature (Suprak et al., 2006), while the plane of elevation and internal/external rotation of the humerus would have no effect on shoulder joint position sense. We further tested a secondary hypothesis that joint position sense would be influenced by the interaction between elevation angle and internal/external rotation angle, as internal and external rotation of the shoulder are known to change tension in musculotendinous and capsuloligamentous mechanoreceptors as elevation angle increases (Blasier et al., 1994; Janwantanakul et al., 2001). This study aimed to better identify differences in shoulder joint position sense between different shoulder postures, which could be important for overhead athletes, especially during rehabilitation.

2. Materials and methods

2.1. Participants

Ten males and ten female healthy adults (mean ± SD age 22.4 ± 2.6 years, weight 73.5 ± 13.0 kg, and height of 1.75 ± 0.04 m) with no history of neuromuscular pathologies or shoulder injury were recruited for this study. Participants self-reported physical functioning score was 99.58% ± 1.85% from the SF-20 general healthy survey, confirming all subjects were healthy (Ware, Sherbourne, & Davies, 1992). All participants provided written consent to the testing procedures approved by the University of Michigan Institutional Review Board (HUM00146884). The dominant arm (defined as the arm the participant used to write) was examined, resulting in the testing of 20 right shoulders.

2.2. Experimental setup

Real-time shoulder kinematic data was collected using Motion Monitor software version 9.33 (Innovative Sports Training, Chicago, IL, USA). The hardware to collect shoulder kinematics included two Optotrack Certus cameras (Northern Digital Inc, Waterloo, ON, Canada), two Optotrack 3020 cameras, a stylus for digitization, and three rigid-body sensors. Glenohumeral angles were tracked and calculated within Motion Monitor and used to control the 3-D position of a cursor in the virtual environment using a custom script. The virtual environment was developed in Vizard development software version 5.8 (WorldViz, LLC) and was computed using a second data collection computer linked to the Motion Monitor computer via ethernet. An HTC Vive virtual reality headset (New Taipei City, Taiwan) displayed this virtual environment using Steam VR. Preference files for each prescribed target position in the virtual environment were randomly loaded using the biofeedback menu within Motion Monitor.

Three rigid-body sensors were attached to the scapula, humerus and thorax to track orientation and position using a series of 4 (scapular) or 6 (humerus and thorax) optoelectronic markers to a 3D-printed construct. The sensors were attached to the thorax over the sternum, the midpoint and most lateral point of the humerus, and the lateral portion of the spine of the scapula near the acromion, similar to surface scapular tracking used in previous research (van Andel, van Hutten, Eversdijk, Veeger, & Harlaar, 2009).

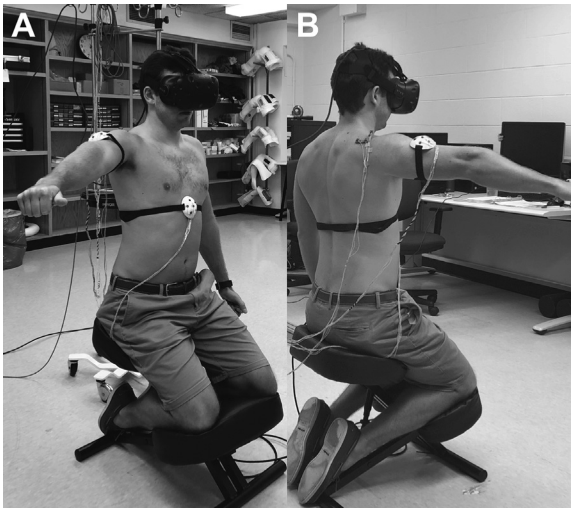

Fig. 1. Shoulder joint position sense was tested using three custom made motion capture sensors attached to the thorax, humerus and scapula. While seated in a kneeling ergonomic chair, participants wore a virtual reality headset which displayed the position of their arm and target locations in three dimensions.

All sensors were attached using double sided tape and Velcro straps.

Our measurement coordinate system was defined using established guidelines by the International Society of Biomechanics (Wu et al., 2005). Following the attachment of sensors, the rotational center of the glenohumeral joint was established using the rotation method, which relies on the rotations of the humerus relative to the scapula to locate the center of rotation (Biryukova, Roby-Brami, Frolov, & Mokhtari, 2000). Bony landmarks were digitized on the thorax, scapula and humerus to establish orientation of segment axes. The thorax coordinate system was established using digitization points at T8, xiphoid process, C7, and the jugular notch. The coordinate system of the scapula was defined using digitization points at the medial border of the spine of the scapula, the inferior angle of the scapula, and the most laterodorsal part of the acromion. The coordinate system of the humerus was established using digitization points of the lateral and medial epicondyles, and the calculated center of rotation of the glenohumeral joint. Consistent with the established axes, Euler angles of Y-Z′-Y″ were used to identify the humerus angles with respect to the thorax.

For the collection, subjects were seated in an ergonomic kneeling chair (Fig. 1). The HTC Vive headset was donned on the head and adjusted to the inter-pupil distance of the participant to ensure clear vision of the targets. Padding was placed around the sides of the headset to ensure the subject could only see what was presented in the headset and was not able to gain visual information about the position of their arm by viewing their arm, the laboratory space or any external light through the sides of the headset. Cords from the VR headset and camera sensors were managed carefully to ensure the cords did not touch the arm to minimize tactile cues. All subjects were shirtless (females wore sports bras) and all jewelry was removed to further eliminate tactile cues.

2.3. Experimental design

All testing was performed in a single two-hour session. Participants performed trials were they reached and replicated targets at 36 different shoulder postures. Each shoulder posture target was a combination of 4 elevation angles (45°, 60°, 75°, and 90°), 3 plane of elevation angles (15°, 45° and 75°), and 3 rotation angles (neutral, 15° internal rotation and 15° external rotation). For each trial, subjects were instructed to keep their elbow straight and locked out and to avoid slouching by sitting tall.

Subjects were explained the protocol and completed practice trials to become comfortable with the visual feedback and task. The beginning of each trial was initiated with a 150 Hz auditory tone. Subjects were presented with red sphere representing one of the 36 randomly prescribed targets within the VR headset (Fig. 2A). A white sphere representing the 3D location of the participant's shoulder was also presented. This cursor was controlled by the real-time movement of the shoulder, with changes in shoulder elevation angle moving the cursor up and down, changes in shoulder plane of elevation moving the cursor left and right, and changes in shoulder internal/external rotation of the arm moving the cursor forwards and backwards (Fig. 2B). The subjects were instructed to keep their elbow straight, as only movements of the shoulder moved the cursor. Subjects were asked to move their shoulder to the proper orientation that would make the white cursor sphere the same size and position of the red target sphere (Fig. 2C). When the subject's shoulder position was within 2° in each plane of the target, another auditory tone was provided, both spheres disappeared, and subjects were instructed to maintain the position of the shoulder for 3 s to memorize the target position. This amount of error is consistent with other studies which used errors between 2° and 5° (King & Karduna, 2014; Suprak et al., 2006; Zanca et al., 2015). When the shoulder position was within the error margin, subjects then relaxed their shoulder down to their side in a neutral posture for two seconds. Finally, subjects were asked to replicate the prescribed target in all three planes of motion, this time without any visual feedback. When subjects felt their shoulder was at the original target position, their contralateral hand pressed an external trigger, ending the trial, and allowing the subject to relax. Two trials were performed at each of the 36 targets in a randomized order,

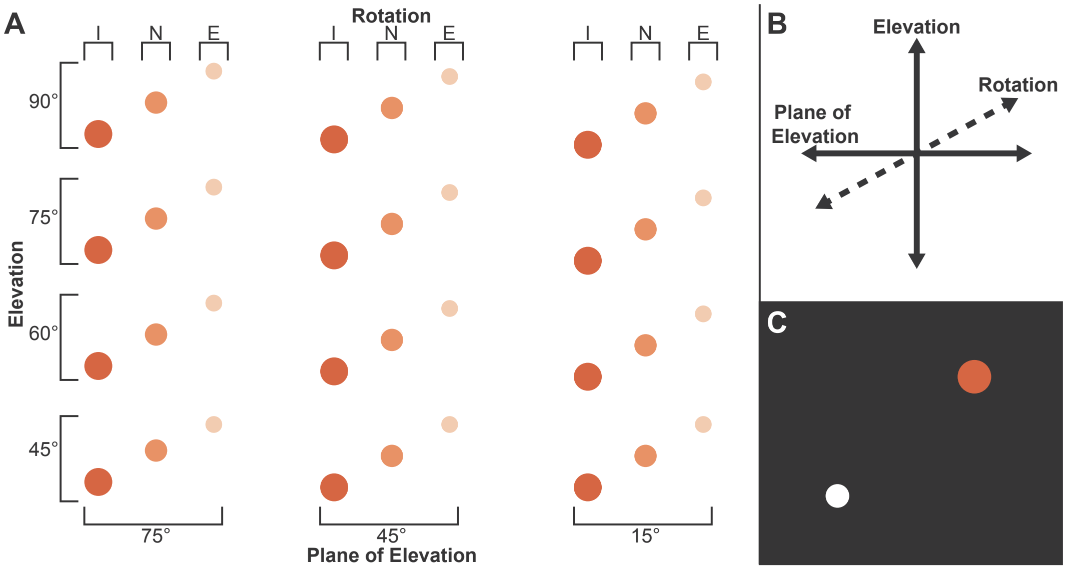

Fig. 2. Thirty-six targets, at elevation angles of 45, 60, 75 and 90, plane of elevation angles of 15, 45, and 75, and rotation angles of 15 internal rotation, neutral and 15 external rotation were presented in a virtual field (A). Participants were able to move a cursor in three dimensions: Elevation moved the cursor up and down, plane of elevation moved the cursor right and left, and rotation moved the cursor forward and backward (B). As viewable in the virtual reality headset (C), the cursor, represented by the white sphere, was controlled by glenohumeral angles and was to be matched to the red target sphere. In this example, the arm must be elevated, moved away from the midline of the body, and internally rotated to match the red target sphere. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

yielding 72 total trials.

2.4. Data analysis

The error, in degrees, between the perceived target position and the original target in each of the three dimensions was calculated using the Motion Monitor software. A resultant error magnitude was then calculated from the individual errors in the elevation, plane of elevation and rotational planes. The resultant error magnitude from the two repeated trials was used to calculate the root mean square (RMS) error. RMS error is a better combination of accuracy and precision and a more conservative measure than taking the average between the two trials (Lin & Karduna, 2017). Precision was further investigated using measures of variable error.

All statistical procedures were performed in SPSS (v24, IBM Corporation, Chicago, IL, USA). Our outcome measure, RMS error, was transformed using the square root and re-examined using the Shapiro-Wilk test to assure normality. We tested the null hypothesis that reductions in RMS error (and thus improved joint position sense) would not be related to changes in elevation angle, plane of elevation or rotation angle. We further examined a secondary null hypothesis that RMS error (and thus joint position sense) would not be influenced by the interaction of elevation angle and rotation angle. A full-factorial repeated measures ANOVA was performed were the square root of RMS error or variable error were the outcome measures and rotation angle, elevation angle, and plane of elevation angle were within-subject factors. A sequential Bonferroni correction procedure evaluated the seven tests associated with ANOVA design against an adjusted alpha level to control for type I error. For reporting, p-values were multiplied by the number of tests performed. Significant main-effects and interactions were further analyzed with Bonferroni-corrected post-hoc comparisons. All ANOVA and post-hoc comparison p-values were multiplied by the number of tests performed and compared to a significance level of $p < 0.05$. Effect sizes for ANOVA tests are reported as eta-squared (η^2) and Cohen's d for pairwise comparisons.

3. Results

Participants were more accurate and less variable as elevation angle was increased, as there was a significant main effect on elevation angle on RMS error ($F_{3,57} = 14.36, p < 0.001, \eta^2 = 0.08$) (Fig. 3A). RMS error decreased as the elevation angle increased. Post-hoc comparisons found RMS error was statistically lower at 90° elevation angle compared to elevation angles of 45° ($p < 0.001$, $d = 0.38$) and 60° ($p = 0.004$, $d = 0.30$). In addition, RMS error was statistically lower at 75° elevation angle compared to 45° elevation angle ($p = 0.007$, $d = 0.29$). RMS error was not significantly impacted by rotation angle ($F_{2,38} = 1.30, p = 0.29$) although participants were observed to be more variable when externally rotated than internally rotated (Fig. 3B). There was also no main effect of plane of elevation angle on RMS error ($F_{2,38} = 0.10, p = 0.91$) (Fig. 3C). There was also a relationship between precision and shoulder posture given a significant main effect of rotational angle on variable error ($F_{2,38} = 3.283, p = 0.048, \eta^2 = 0.01$). Across all conditions, there was a lower mean (SE) variable error was significantly lower in neutral (1.4 (0.1)°) and internally rotated postures

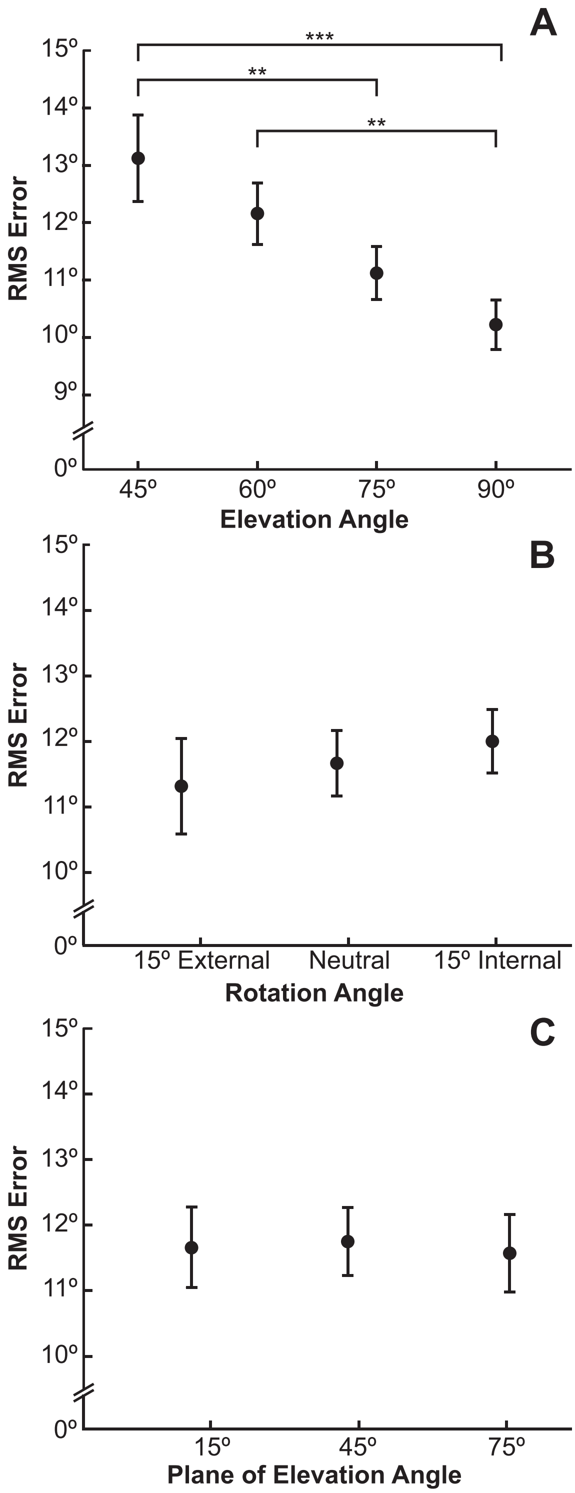

Fig. 3. (A) Increases in elevation angle improved shoulder joint position sense in the shoulder, while which was measured as the root mean squared (RMS) error of the magnitude of the repositioning error. Increases in (B) rotation angle and (C) plane of elevation angle had no effect on joint position sense. Bars represent mean RMS error ± standard error (* = significance at $p < 0.05$, ** = significance at $p < 0.01$, and *** = significance at $p < 0.001$).

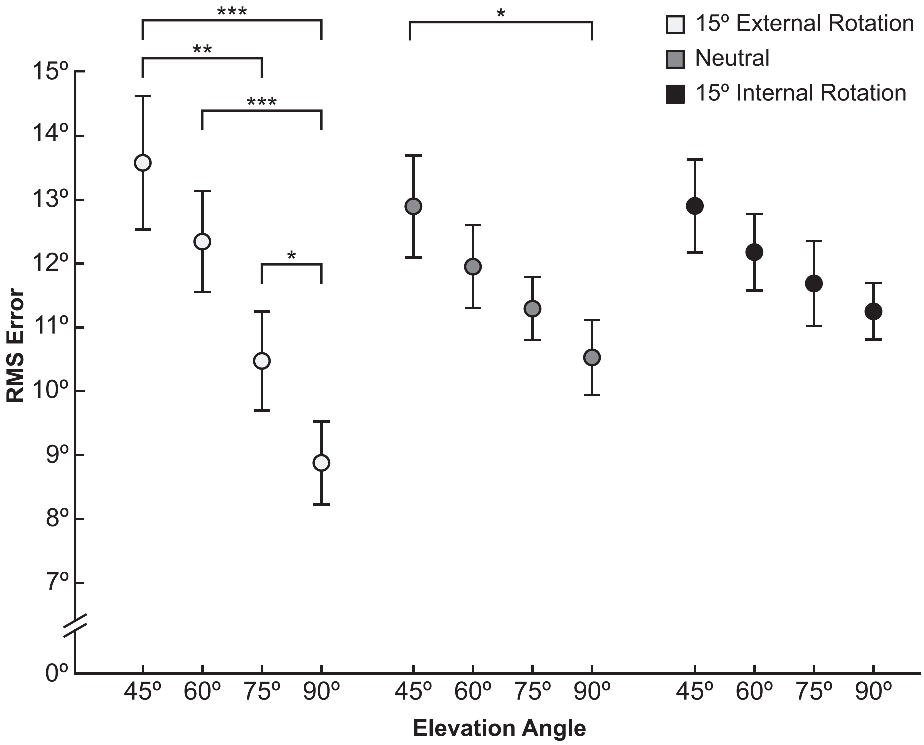

Fig. 4. When the shoulder was externally rotated, increases in elevation angle improved joint position sense in the shoulder, which was measured as the root mean squared (RMS) error of the magnitude of the repositioning error. When the shoulder was in a neutral posture or internally rotated, increases in elevation angle did not improve joint position sense as much as external rotation did. Bars represent mean RMS error ± standard error (* = significance at p < 0.05, ** = significance at p < 0.01, and *** = significance at p < 0.001).

(1.4 (0.08)°) than externally rotated postures (1.7 (0.1)°). This indicates lower precision at reproducing the targets when participants were externally rotated. No other factors or interactions, including elevation angle, reached significance for variable error.

We further examined how joint position sense was affected by the interaction between elevation angle and rotation angle. There was a statistically significant interaction between rotation angle and elevation angle on RMS error ($F_{6,114} = 4.20$, $p = 0.004$, $\eta^2 = 0.02$). The effect size for this interaction effect was lower that the effect size observed above for the main effect of elevation angle on RMS error. As elevation angle increased, participants were more accurate (e.g. lower RMS error) when the arm was externally rotated 15° when compared to neutral or internally rotated 15°, but exhibited greater variability when externally rotated than internally rotated (Fig. 4). Post-hoc comparisons showed that when the arm was externally rotated 15°, the RMS error was statistically lower at 90° elevation ($p < 0.001$, $d = 0.89$) and 75° elevation ($p = 0.002$, $d = 0.55$) than compared to 45° elevation. In addition, external rotation produced RMS errors that was statistically lower at 90° elevation than compared to 60° elevation ($p < 0.001$, $d = 0.72$) and 75° elevation ($p = 0.02$, $d = 0.43$). When the arm was in a neutral posture, there was only a single significant difference, between elevation angles of 45° and 90° ($p = 0.02$, $d = 0.43$). There were no statistically significant differences in RMS error when the arm was elevated and internally rotated 15°. Participants were observed to be more consistent but less accurate when internally rotated. The remaining two-way interactions found between rotation and plane of elevation angle or plane of elevation and elevation angle and three way interactions between rotation, plane of elevation, and elevation angle were immediately rejected based on the sequential Bonferroni correction procedure.

4. Discussion

The current study investigated 3-D shoulder proprioception using a target replication task that employed a novel virtual reality feedback to recreate 3-D shoulder joint positions. Our results indicated that joint position sense, measured by RMS error in a target matching task, was significantly affected both by elevation angle and the interaction between rotation angle and elevation angle. Joint position sense was significantly improved as elevation angle was increased. This enhancement of joint position sense with increased elevation angle was further affected by external rotation of the shoulder.

Increases in elevation angle produced decreased RMS error in target matching tasks. This is in agreement with previous studies that have shown RMS error decreases as elevation angle approaches 90°, and then increase again with elevation angles greater than 90°. While these findings could be attributed to increased torque applied to the shoulder due to gravity leading to greater muscle activation and greater proprioceptive feedback (Suprak et al., 2006), changes in external shoulder loads only have a small effect on joint position sense (Suprak, Osternig, van Donkelaar, & Karduna, 2007). Controlling for the effects of gravity using a tilting chair to compare the same elevation angles has shown that the angular position of the shoulder has a greater effect on joint position sense than torque at the shoulder (Chapman et al., 2009). The current study further supports the importance of angular position of the upper extremity on shoulder joint position sense given the significant interaction between elevation angle and rotational angle. There were no differences in joint torque due to gravity as the arm was elevated in three different axial rotation postures. We observed improved joint position sense when the arm was elevated in an externally rotated posture. These results agree with previous research that found the detection of external rotation significantly more sensitive than the detection of internal rotation using passive repositioning (Blasier et al., 1994).

While shoulder joint position sense is not improved by increased muscle tension as elevation angle increases, the observed decrease in RMS error during external rotation as elevation angle increases is likely due to greater afferent feedback from increased muscle tension in the shoulder joint caused by external rotation. While joint position sense and its relation to muscle tension during elevation has been previously examined (Chapman et al., 2009; Suprak et al., 2007), it has not been examined during external rotation. Capsuloligamentous mechanoreceptors are only active when the joint is at extreme ranges of motion (Rymer & D'Almeida, 1980), which were not achieved in this study. Therefore, musculotendinous mechanoreceptors such as muscle spindles and golgi tendon organs, which measure the changes in length and tension of the muscle, are likely the primary contributors to joint position sense at these tested mid-ranges of motion (Suprak, 2011). Since the deltoids and supraspinatus are primarily responsible for increases in elevation angle (Kuechle, Newman, Itoi, Morrey, & An, 1997), and the teres minor and infraspinatus are primarily responsible for external rotation about the shoulder joint (Kuechle et al., 2000), the musculotendinous mechanoreceptors from these muscles must be active during elevation and external rotation. This activation in the musculotendinous mechanoreceptors as a result of tension in the muscles leads to increased afferent feedback from muscle spindles and improved joint position sense.

As the arm is elevated, the arm becomes closer to the end range of external rotation in axial rotation (Ludewig et al., 2009). Previous studies have found joint position sense to improve at end ranges of motion where there is more tension on the restraints to movement (Janwantanakul et al., 2001) and as the limits of external rotation are approached, compared to the middle range of motion (Blasier et al., 1994; Janwantanakul et al., 2001). In the current experiment, the amount of external rotation angle examined was selected to ensure the angle could be reproduced at all prescribed shoulder postures, and therefore was never at the end ranges of motion. However, as the arm becomes more elevated, the shoulder becomes closer to the end range of external rotation compared to when the shoulder is less elevated, which may be a cause of improved joint position sense.

As many sports and activities of daily living require joint position sense to complete a task, the ability to elevate and externally rotate is important for adequate shoulder proprioception and control. These findings can also be applied to rehabilitation from shoulder injury. When an injury occurs that limits external rotation at the shoulder, not only is the rotational range of motion reduced, but shoulder proprioception as well. Therefore, rehabilitation on a postoperative shoulder should incorporate exercises that return the full rotational range of motion of the shoulder, but also to properly retrain the dynamic neuromuscular control of the shoulder. A proper progression including activities targeting joint position sense, dynamic joint stabilization, reactive neuromuscular control, and functional movements should be incorporated as this type of progression targets motor pathways, stabilization and neuromuscular control of the shoulder, which will allow the joint to return to proper anatomical and proprioceptive health (Lephart & Henry, 1996; Lephart et al., 1997).

This study supports the usefulness of virtual reality in the examination of joint position sense. While a variety of experimental protocols exist to test shoulder joint position sense, the use of virtual reality allows shoulder joint position sense to be tested in all three planes of motion at the shoulder during active joint replication. To our knowledge, this is the first study that has examined joint position sense in all three planes, as previous research has only investigated elevation angle and plane of elevation, excluding the rotational component of the shoulder (Suprak et al., 2006). The virtual environment allows targets and cursors to be placed in three dimensions using depth as an additional plane, not available in a normal head mounted display. While the repositioning error was 3°–6° greater than previous studies, the trends of the current data are in agreement with previous studies (Suprak et al., 2006). This increase in repositioning error is expected, as this 3D novelty makes the protocol more complex with an additional plane to reposition in. With results of this study in agreement with previous results using established testing protocols, it further supports the novel use of this virtual reality testing protocol to examine joint position sense.

However, there were some limitations to this approach. While we examined thirty-six different arm postures, no elevation angles were tested above 90°. Previous studies have found joint position sense will begin to decrease as the arm is elevated above 90° (Suprak et al., 2006). Future work is needed to examine if the interaction between external rotation and elevation angle exists as the arm is overhead. The participants in this study were young and in good health and therefore these results may not translate to clinical populations. Differences in joint range of motion between subjects were also not examined. If certain subjects had limited rotational range of motion, then the rotation targets may be closer to their end ranges of motion, resulting in improved joint position sense.

In conclusion, joint position sense of the shoulder improved as the arm was elevated and externally rotated. These improvements in joint position sense are likely due to a combination of increased tension in muscles responsible for elevation and external rotation, increased tension in the capsuloligamentous mechanoreceptors at the shoulder, and external rotation that is closer to end range of motion at greater elevation angles; all leading to increased afferent feedback to improve shoulder proprioception. These results further support the use of joint position sense rehabilitation exercises following injury to regain neuromuscular control and stability of the shoulder. In addition, orthopedic issues or injuries that prevent external rotation at the shoulder should be treated seriously as this will inhibit shoulder proprioception which is important in any sport or activity requiring movement of the shoulder outside the field of vision.

Acknowledgements

We acknowledge financial support from the Marie Hartwig Research Fund at the University of Michigan School of Kinesiology, and the technical assistance of Santiago de Grau and Ian Hoelker at Innovative Sports Training (Chicago, IL).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.102508.

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