Three-Dimensional Repositioning Tasks Show Differences in Joint Position Sense between Active and Passive Shoulder Motion

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ABSTRACT: Proprioception is important in maintaining shoulder joint stability. Previous studies investigated the effects of unconstrained multiplanar motion, with subjects able to move freely in space, on repositioning tasks for active shoulder motion but not passive motion. We sought to further explore joint position sense with 3D passive, robot-guided motions. We hypothesized that target repositioning error would be greater in the case of passively placed targets than for actively placed targets. To investigate, 15 healthy individuals participated (8 female, 7 male), who were at most 6 ft (183 cm) tall to accommodate the equipment, and who had no history of shoulder injury, surgery, or significant participation in throwing sports. Target orientations were centered at 44° of elevation and 32° of horizontal rotation from the frontal plane. Two sets of 10 trials were performed. The first set involved active placement followed by active replacement, and the second set involved passive, robot-guided, placement followed by active replacement. Repositioning error was greater following passive placement than active placement ($p < 0.001$). These results further our understanding of the differences between active and passive joint position sense at the shoulder. © 2011 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 30:787–792, 2012

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The shoulder, or glenohumeral joint, provides the arm with a large range of motion,[1] yet this joint possesses very little intrinsic stability, resembling a ball on a plate more than a ball in a socket. Most stability in the shoulder is provided by the ligaments and muscles surrounding the joint. Proper muscle activation is required to maintain positioning of the humeral head in the glenoid fossa.[2] Adjustments are continuously made to glenohumeral joint position based on feedback information from proprioceptive receptors in the muscles, tendons, ligaments, and receptors in the skin.[3,4] Impaired proprioception function can lead to shoulder injury.[5]

Proprioception is a complex entity with many interacting components. The brain uses efference copy to initiate and verify active motions.[6–8] Such verification requires information about musculoskeletal motion sent back to the brain by a variety of sensory receptors in the muscles and skin. The current belief is that muscle spindles, movement encoders in parallel with the muscle, are the predominant proprioceptors with important contributions from cutaneous receptors.[3,7] Muscle spindle intrafusal fibers in the shortening muscle contract during active motion, possibly to maintain muscle spindle sensitivity.[3]

Proprioception is used in the assessment of joint injury, reconstruction, and rehabilitation.[5] Injury tends to decrease proprioceptive ability, while surgical reconstruction seems to restore it.[4] In research, such assessments are often performed using position matching tasks. The contralateral limb can be involved using simultaneous mirroring movements, or the ipsilateral limb can be reused by recalling the placement position from memory. When the individual uses the ipsilateral limb to match a joint position, active or passive placement at a joint position is followed by active or passive replacement. Clinically, passive motion is used when proprioceptive testing must be performed on damaged or non-functional muscles.[9]

In most proprioception studies, motions are 2D; subjects' movements are confined to only the prescribed plane of motion.[2,10,11] However, daily activities are seldom performed in such a restricted fashion. Recent studies used normal 3D motion to explore shoulder proprioception in a less restricted environment.[12–14] However, these studies were limited to active tasks and did not investigate joint position sense during passive movements. Adamovich et al.[15] performed a study of unconstrained, multi-planar motion for tasks using active placement followed by active replacement (AA) and passive placement followed by active replacement (PA), and found the AA condition to be more accurate. Active motion was performed by having the investigator "slightly pushing the subject's arm with his hand," and passive motion was completely controlled by the investigator; in both conditions visual feedback was eliminated. These aspects are similar to the present study with the exception that we incorporated visual guidance during active placement and robot-assisted passive motion.

Our goal was to compare proprioception in 3D repositioning tasks for active replacement following passive, as well as active, placement. Proprioception during passive motion is less accurate than during active motion due to altered motor planning and intrafusal muscle coactivation.[15] Thus, we hypothesized that greater repositioning error would be observed in the PA case than in the AA case.

METHODS

Participants

Fifteen healthy, right arm dominant individuals (eight females, seven males; age = 22.5 ± 4.8 years; height = 170.7 ± 8.4 cm; body mass = 65.1 ± 12.2 kg) participated. All subjects read and signed an informed consent document approved by our

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University's Institutional Review Board. Individuals were included only if they had no history of shoulder injury, surgery, or significant participation in throwing sports. Due to equipment restrictions, they could be at most 6 ft (183 cm) tall. Dominance was assigned to the arm that each subject stated he/she used to throw a ball.

Equipment

Subjects were seated in a wooden kneeling chair (F1450, Jobri, Konawa, OK), and, with the exception of the dominant arm, were otherwise unrestrained. A cast made of Orthoplast® was placed across the dominant elbow to maintain full extension (Fig. 1). No wrist or hand restraints were used, but subjects were instructed to extend their fingers and keep their thumb pointing upward (Fig. 1) in accordance with previous studies.[13] This was done in both active and passive trials to maintain consistency. A head mounted display (HMD; Z800, eMagine, Bellevue, WA) provided visual presentation of the target orientations and eliminated visual cues while moving during replacement tasks. This was the only guidance subjects received during the positioning phase.

The coordinate system was established according to the recommendations of the International Society of Biomechanics.[16] A sensor was placed on the skin above the acromion process, on the lateral side of the humerus near the midpoint, and on the sternum about 1–3 cm below the sternal notch. The acromial sensor was only used to establish the coordinate system; it was removed prior to collecting data to minimize cutaneous feedback to the subject. Anatomical coordinate systems were constructed in the software relative to the physical markers by recording bony landmarks: C7, T8, sternal notch, xiphoid process, and the medial and lateral humeral epicondyles. The center of rotation at the humeral head was established according to Suprak et al.[13] Data were collected at 40 Hz using a magnetic tracking system (Polhemus Fastrak, Colchester, VT).

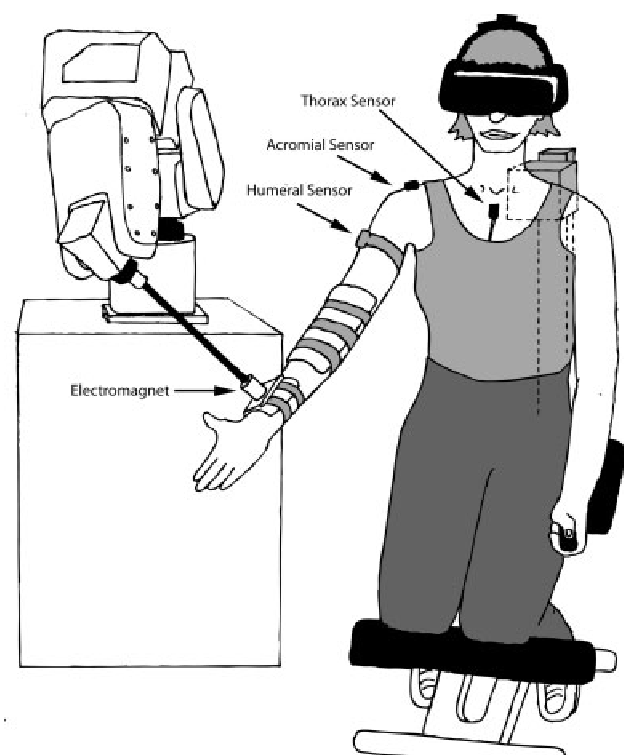

Figure 1. Components of the experimental setup included the electromagnetic tracking device with three sensors, HMD, elbow cast, wrist attachment, kneeling chair, robot, and safety shut-off button.

To actuate the passive motion, a robotic arm (LR mate 200iB, FANUC Robotics, Rochester Hills, MI) was attached to the subject's dominant arm at the wrist via a 35 cm shock-absorbing rubber linkage. The robot has a repeatability of ±0.04 mm. An electromagnet (EM175L-12-122, APW Company, Rockaway, NJ) on the robot interfaced with a small steel plate worn on the subject's wrist, serving as the mechanical linkage between the two. Throughout all testing, subjects held a shut-off button for the electromagnet (EM) linkage in their non-dominant hand (Fig. 1), and were instructed to press the button if they wished to be released from the robot. However, no subject pushed the button during data collection. The robot moved the subject's arm at ~6.5°/s at the shoulder, maintaining a right angle between the linkage and the arm. The linkage was disconnected to allow unrestricted arm motion.

Protocol

Warm-up and stretch activities were performed at the beginning of each data collection.[13] After warm-up, subjects removed their shirts (females wore athletic sports bras). In a previous study from our laboratory using the same AA protocol, we found no significant effect of plane on repositioning errors ($p = 0.26$). While an overall effect of elevation angle was found, when the data were analyzed at low angles, no significant effect occurred on repositioning errors ($p = 0.17$). Additionally, the highest reliability (ICC = 0.69) was at the target position of 35° of plane and 50° of elevation. Based on this information (and the limitations of the robot workplace), we selected five target orientations (plane/elevation angles) as follows: 30:35, 30:45, 30:55, 25:45, 35:45. The five target orientations were randomized twice for each subject to generate a single set of 10 target orientations. These orientations represented positions of the humerus relative to the thorax, but were converted to a global coordinate system, i.e., a lab-based coordinate system that was common to the robot and magnetic tracking device.

The first of two sets of ten trials consisted of active arm positioning at each target orientation, followed by active arm repositioning. Subjects performed practice trials viewed first on a computer monitor for ease of instruction, then again after donning the HMD. Each trial began with the subject's arms at the sides. For the first positioning movement of a pair, the subjects were instructed to move the dominant arm while focusing on upper arm orientation. When the upper arm was far from the target, subjects were guided by bars that would appear on the top, bottom, right, or left side of the screen. These bars indicated in what direction the subject should move the dominant arm. For example, bars on the top and on the right of the screen would indicate the arm should be moved up and to the right of its current position to approach the target. When the subject's arm was within 5° of the target orientation, a floating red dot appeared as a 2D, real-time representation of upper arm orientation. The dot was then guided to a small square at the center of the screen, which represented the target orientation ±1°. When this orientation had been maintained for 1 s, a tone sounded, and a black screen was displayed. After an additional 5 s under these conditions, the word "relax" was sounded, at which point the subjects lowered their arm to their side. Then after 6 s, with the screen still dark, the word "return" was sounded, and subjects replaced their arm to what they believed was the target orientation. At this point subjects indicated verbally that they were at the target orientation, and the researcher pressed a trigger to mark the data.

A 10 min rest period was observed between the two sets of trials, during which the HMD and elbow cast were removed, to be replaced before resuming data collection. The subject performed a practice trial without the HMD to ensure comfort with the robot operations.

The final set of 10 trials involved passive, robot-guided placement at the target orientation, followed by active replacement to the target orientation. The path of the robot was set so that it approximated the path of the shoulder during the corresponding active trial of that subject. Subjects began with their dominant arm at their side, and the robot attached at their wrist. For safety, the subject had to acknowledge they were ready to begin before each trial. During the robot movement, the HMD showed the same targeting display as during active target positioning. Just as before, 1 s after the robot had reached the target orientation, a black screen was displayed. Then, after 5 s the word "relax" sounded, and the robot returned the subject's arm to their side. At this point, the robot was disconnected, and the active replacement phase proceeded as before.

Data Analysis

3D position and orientation data for the thoracic and humeral markers were converted to plane and elevation angles. Elevation angle (the amount of shoulder elevation) was the vertical component of the target orientation, while plane angle was the horizontal component measured from the frontal plane. The plane and elevation angle differences were computed as the replacement angle minus the target position angle for each trial. Positive angle difference indicated overshoot in plane and elevation angle. Additionally, at each target orientation, a vector passing through the center of the humeral head and the midpoint between the medial and lateral epicondyles was calculated. For each trial, the angle between the placement and replacement vectors indicated the absolute deviation and was termed the vector difference.

The targets were presented for the humerus with respect to the global coordinate system regardless of the thorax orientation, as necessitated by the equipment configuration. Since the thorax was not constrained, we obtained several orientations for the humerus relative to the thorax for each target orientation in the global coordinate system. However, the relationship of interest was the humerus moving with respect to the thorax in a subject-based coordinate system. Therefore, motion data were analyzed in terms of the subject-based coordinate system with the thorax fixed and the humerus moving relative to it. Due to the constraints of the robot workspace, the flexibility of the shock-absorbing linkage, and the fact that thorax was not fixed in the global coordinate system, the presented active and passive target orientations differed somewhat. The target orientations were, on average, different for the two conditions by 2.0 and 7.4° for plane and elevation, respectively. The variability of these differences was 9.3 and 6.4°, respectively.

Statistical Analysis

The data for all 10 trials revealed a mean target orientation of 32° of plane rotation and 44° of elevation. Due to high individual variability, outliers were screened and removed from the analysis. An arbitrary range was established to capture the most representative pool of data; only target orientations within ±10° of the mean plane angle and ±20° of the mean elevation angle were kept. This resulted in eliminating the first subject's data. The remaining subjects (eight female/six males) each lost, on average, one active and two passive trials. Two-tailed paired t-tests were performed to compare the two conditions (AA or PA) with the following variables: constant and variable error of plane and elevation angle difference and constant error of vector difference. Constant error was calculated as $\sum(x-0)/n$, and variable error was calculated as $\sqrt{\sum(x-M)^2/n}$, where x is the replacement difference, M is the mean replacement difference, and n is the number of trials.[17] Given the five analyses, a Bonferroni correction was used to obtain a more conservative alpha level of 0.01. SPSS (Version 17, SPSS, Chicago, IL) was used to perform the analysis.

RESULTS

For the passive condition compared to the active condition, all subjects had higher vector differences (Fig. 2), based on a comparison of the constant error of the vector difference for the two conditions ($p < 0.001$, ES $= 0.72$, power $= 0.78$, $\alpha = 0.01$). For shoulder elevation, all subjects overshot the target orientation following passive placement (Fig. 3). For the elevation angle difference, constant error was significantly higher in the PA condition ($p < 0.001$, ES $= 0.74$, power $= 0.82$, $\alpha = 0.01$), but variable error was not ($p = 0.050$). For the plane angle difference,

Table 1. Mean and Standard Deviation of the Variables Used in the Final Statistical Analysis

	Active-active (deg)		Passive-active (deg)		
Variable	Mean	SD	Mean	SD	p-value
Constant error of plane angle difference	0.4	2.8	5.9	7.8	0.022
Constant error of elevation angle difference[a]	3.1	4.0	12.9	5.0	<0.001
Constant error of vector difference[a]	6.0	2.6	15.2	5.7	<0.001
Variable error of plane angle difference[a]	3.7	1.4	5.7	2.1	0.008
Variable error of elevation angle difference	3.2	1.0	4.0	1.4	0.050

[a]Indicates that the passive condition significantly differs from the active condition for a significance level of 0.01. Active-active indicates active target orientation placement followed by active replacement. Passive-active indicates passive placement followed by active replacement.

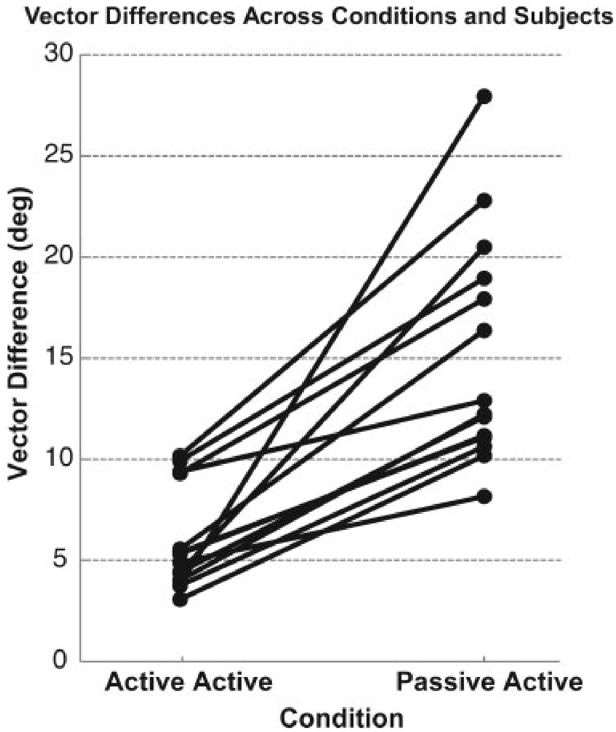

Figure 2. Vector difference: the angle between the arm vector (oriented along a line from the center of the humeral head to a point between the medial and lateral humeral epicondyles) at target orientation placement, and the arm vector at replacement for both conditions. The active condition involved active placement followed by active replacement, while the passive condition involved passive placement followed by active replacement. The increased vector difference in the passive condition was significant ($p < 0.001$).

constant error was not significantly different in the PA condition ($p = 0.022$), but the variable error was significantly greater ($p = 0.008$, ES $= 0.49$, power $= 0.22$, $\alpha = 0.01$). These results are summarized in Table 1.

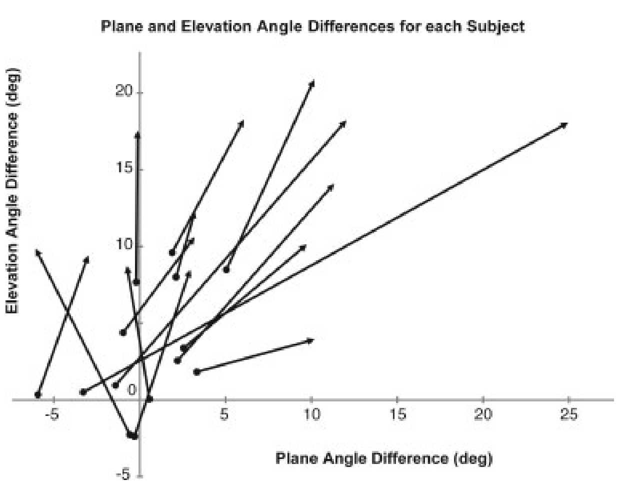

Figure 3. Elevation angle difference versus plane angle difference for active placement followed by active replacement (dots) and for passive placement followed by active replacement (arrow heads). The consistent overshoot was significant. Positive values indicated vertical overshoot in elevation and horizontal overshoot in plane rotation.

DISCUSSION

This study investigated proprioceptive tasks involving passive and active placement followed in both cases by active replacement. We hypothesized that a higher repositioning error would occur for trials that involved passive placement. This was partially supported by our data (Table 1) that showed significantly higher vector differences and vertical overshoot in the PA trials. Subjects were less accurate in vertical repositioning in the PA condition, though they were not less precise. The hypothesis is not well supported for horizontal repositioning; subjects were not less accurate in horizontal repositioning in PA trials, though they were less precise. A study of multi-planar movement compared AA and PA pointing tasks.[15] Similar to the present study, significant differences occurred in variable error of the plane angle difference between conditions ($1.7 \pm 0.1^\circ$ for AA and $2.5 \pm 0.2^\circ$ for PA) and no significant difference occurred in the constant error of the plane angle difference (values range from $-2.2 \pm 0.9^\circ$ to $1.2 \pm 0.6^\circ$ for AA and $-3.3 \pm 1.6^\circ$ to $1.6 \pm 1.2^\circ$ for PA). However, in contrast to our study, significant differences were found in variable error of the elevation angle difference ($2.01 \pm 0.1^\circ$ for AA and $2.4 \pm 0.2^\circ$ for PA) but no significant difference occurred in constant error of the elevation difference ($+1$ to 2° for AA and -1 to -2° for PA).

Two studies conducted trials that examined only the horizontal plane. Lonn et al.[11,18] found no difference between AA and PA conditions, though AA errors were consistently lower than those observed in our study. In contrast, Laufer et al.[9] observed a significant difference between conditions ($0.2 \pm 9.4^\circ$ for AA versus $2.6 \pm 11.2^\circ$ for PA) for shoulder and elbow movements in the horizontal plane. Though these studies are of purely planar motion, the overall pattern of differences between movement conditions is the same in the horizontal plane as in the multiplanar studies.

Vertical overshoot was observed during replacement for both AA and PA conditions. Furthermore, subjects exhibited significantly greater vertical overshoot following passive than following active placement (Fig. 3). Vertical overshoot was also observed by Adamovich et al.;[15] however, they found no significant difference between AA and PA conditions. This may be due to the fact that they permitted both elbow and shoulder flexion, thus enabling mutual compensation by both joints to achieve a target orientation, while in our study the elbow was locked in flexion, forcing shoulder motion only.

Vertical overshoot was higher in the PA condition. Values for the AA condition fell just below ranges of vertical overshoot previously reported in shoulder repositioning studies: 4–9°.[13–15] The higher vertical overshoot in the PA condition could be due to slower passive placement (6.5°/sec) by the robot. During robotic placement, subjects moved 4.5x slower than during replacement, while in the purely active trials they only moved 1.6x slower during placement than during replacement. Subjects may have overshot the target orientation due to this greater difference between placement and replacement movement velocities. Moving faster during replacement while using their placement time as a guide could cause subjects to overestimate their position.

In terms of horizontal overshoot, no difference was found between AA and PA positioning. However, larger horizontal overshoots were reported when subjects' arms are passively moved to a target, compared to when their arms are actively moved.[9,15] We might not have observed these differences because our target positions had a greater vertical (20°) than horizontal range (10°), as suggested by a significantly higher variability in plane angle difference in the PA compared to AA condition.

During passive movement, the responses of muscle spindles can be altered by previous activity of the parent muscle, which may suggest that the increased errors observed in PA positioning tasks are due to alterations of the resting discharge of the spindles caused by the preceding active motions.[19] However, in recent years, efference copy itself has been proposed as an important component of joint position sense.[7,8,20–22] Therefore, higher repositioning errors observed in the PA tasks might be due to the absence of activity of efference copy during passive motion which leads to an altered sense of position.

Our results may have clinical importance; robot-assisted therapy is an increasingly beneficial part of physical rehabilitation due to its cost effectiveness, convenience, and potential to yield better results in some cases. Many robotic systems used in therapy have the ability to provide passive, assisted, and resisted motion.[23] But what specifically leads to the potentially greater restoration of motor control following robot-assisted therapy has yet to be discovered.[24] Our results underscore the importance of elucidating the differences between active and passive motion to understand and ultimately improve robot-assisted therapy. To address whether proprioception in active motion is indeed more accurate than passive motion, future research should incorporate a robotic component that enables passive placement with passive replacement test conditions. For example, subjects could use a joystick to control the robot-actuated passive movements in their contralateral limb. This would permit direct evaluation of the ability to recall shoulder position during passive motion. Such a study could begin to compare the true accuracy of active and passive joint position sense in 3D shoulder motion.

Our study has limitations. First, to maintain consistency with the active condition, subjects were instructed to keep their thumb pointed upward in the passive condition. Since muscle contractions are not often localized, this could have led to active contraction at the shoulder. Subjects were also instructed to relax their dominant shoulder during the passive manipulations. The relaxed state was not directly verified or monitored, but had subjects been resisting the robot, either the EM junction would have broken, or movements in the flexible wrist attachment would have made it obvious. None of these indicators were observed.

Second, subjects were not explicitly instructed to move at a trained speed; they were only instructed to move slowly. Consequently, active motions occurred at different speeds from the passive motions performed by the robot, which always moved at a fixed speed. The time to reach the target in either condition was less variable than the time spent moving back to the starting position. Compared to active placement, it took 2 s longer to passively move to the target orientation and 3–11 s longer to return to the start position. It is reasonable to suspect that these differences had some influence on the subjects' perception of target orientations.

Third, the majority of proprioceptive studies involving passive motion utilize passive placement followed by passive replacement. Such a protocol enables a direct assessment of the accuracy of passive proprioception. Our setup prevented inclusion of a passive replacement component; therefore, the results cannot be used to directly compare the accuracy of active and passive proprioception. However, our protocol and results effectively exposed a difference between active and passive motion, and are relevant to clinical assessments of proprioception that use passive placement followed by active replacement.

In conclusion, proprioceptive information is significantly different between passive and active motion in subject-determined, 3D movements. This difference is mainly due to a tendency for subjects to over-estimate arm elevation during passive movements. These findings may have importance in the field of shoulder rehabilitation and to the growing use of passive, robot-assisted therapies. Further study is required to better understand the nature of the difference between active and passive shoulder motion.

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