

Functional Multijoint Position Reproduction Acuity in Overhead-Throwing Athletes

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Context: Baseball players rely on the sensorimotor system to uphold the balance between upper extremity stability and mobility while maintaining athletic performance. However, few researchers have studied functional multijoint measures of sensorimotor acuity in overhead-throwing athletes.

Objective: To compare sensorimotor acuity between 2 high-demand functional positions and among planes of motion within individual joints and to describe a novel method of measuring sensorimotor function.

Design: Single-session, repeated-measures design.

Setting: University musculoskeletal research laboratory.

Patients or Other Participants: Twenty-one National Collegiate Athletic Association Division I baseball players (age = 20.8 ± 1.5 years, height = 181.3 ± 5.1 cm, mass = 87.8 ± 9.1 kg) with no history of upper extremity injury or central nervous system disorder.

Main Outcome Measure(s): We measured active multijoint position reproduction acuity in multiple planes using an electromagnetic tracking device. Subjects reproduced 2 positions: arm cock and ball release. We calculated absolute and variable error for individual motions at the scapulothoracic, glenohumeral,

elbow, and wrist joints and calculated overall joint acuity with 3-dimensional variable error.

Results: Acuity was significantly better in the arm-cock position compared with ball release at the scapulothoracic and glenohumeral joints. We observed significant differences among planes of motion within the scapulothoracic and glenohumeral joints at ball release. Scapulothoracic internal rotation and glenohumeral horizontal abduction and rotation displayed less acuity than other motions.

Conclusions: We established the reliability of a functional measure of upper extremity sensorimotor system acuity in baseball players. Using this technique, we observed differences in acuity between 2 test positions and among planes of motion within the glenohumeral and scapulothoracic joints. Clinicians may consider these differences when designing and implementing sensorimotor system training. Our error scores are similar in magnitude to those reported using single-joint and single-plane measures. However, 3-dimensional, multijoint measures allow practical, unconstrained test positions and offer additional insight into the upper extremity as a functional unit.

Key Words: upper extremity, joint position sense, proprioception, throwing athletes

Overhead-throwing athletes suffer from both acute and chronic upper extremity injuries, including impingements, tendinopathies, strains, subluxations, and dislocations^{1,2} at an alarming rate.^{3,4} Declines in function of the sensorimotor system (SMS) are associated with such acute and chronic upper extremity injuries.^{5,6} Without intervention, these events can become cyclic, resulting in further decline of the SMS, mechanical dysfunction, joint inflammation, and injury.^{7–9} To optimally evaluate, treat, and rehabilitate injuries to the overhead-throwing athlete, we must better understand the role of the SMS in upper extremity function and dysfunction. The methods used to investigate this topic, however, lack multiplanar and multijoint functional measures and positions. Therefore, our ability to apply research findings to a population such as overhead-throwing athletes is limited.¹⁰

The SMS is the collective term used to describe the physiologic integration of the neurosensory and neuromuscular

processes, which provide the body with coordination of movement and stability.⁷ This system encompasses afferent and efferent components as well as the processing and integration of these signals by the central nervous system.^{11,12} Precise SMS function is necessary for effective motor program development and to optimize the constant feedback-adjustment interplay during complex motion.^{7,13} Accurate development and execution of motor plans require precision of all 3 components of the SMS. Afferent signals arising from mechanoreceptors must provide the central nervous system with timely and accurate information regarding joint position, motion, muscle tension, resistance, and pain. The central nervous system must correctly interpret this information and then initiate an appropriate efferent response. Interpretation of afferent signals takes place either at the spinal level, through a reflex activation, or at higher levels after transmission to the brain stem and cerebral cortex. The central nervous system inte-

grates afferent information into waiting motor plans to best achieve the desired response. The integration and comparison between afferent input and motor plans are constant and dynamic, giving rise to ever-adapting efferent responses. This continuous process provides us with our neuromuscular control and facilitates dynamic joint stability.^{7,8}

As our understanding of the SMS evolves, clinicians are beginning to appreciate the importance of its optimal function. Findings from studies of the lower extremity suggest that patient satisfaction and functional outcome correlate better with measures of SMS function than with the traditional measures of joint motion or laxity.^{14–16} Additionally, rehabilitation protocols addressing deficits in SMS function help to prevent or minimize future lower extremity injury.^{17,18} Compared with our knowledge about the lower extremity, however, our understanding of relationships between the SMS and upper extremity function, dysfunction, or rehabilitation is limited. However, provided the inherently unstable nature of the shoulder, dynamic stability is undoubtedly paramount for proper function.^{19,20} Therefore, the SMS must play an integral role in optimal upper extremity function.

Investigators studying the role of the SMS in upper extremity function have focused on specific submodalities of proprioception, including kinesthesia (threshold to detection of motion), joint position sense (active or passive), and neuromuscular control (stability and balance). These characteristics are typically measured in single joints and single planes of motion, often restricting the motion of both distal and proximal joints.^{5,19,21–26} In upper extremity research, many authors focus on single-plane motions of the glenohumeral joint,^{5,21–26} using isokinetic dynamometers to measure active or passive joint position sense^{26–29} or threshold to detection of passive motion.^{5,21–23,25} Many testing techniques require the subject to be either strapped to a chair in a seated position^{10,23} or lying supine.^{5,19,21,25,29} The functional application of much of this research is limited by these restrictive techniques.

Although observations of single joints and planes of motion may hold particular importance, more functional testing of the upper extremity is warranted.^{10,30} Because the upper extremity has a vast range of motion and numerous degrees of freedom, such functional measures of SMS function necessitate multidimensional and multijoint testing methods.

Our purposes were to (1) describe and compare the acuity of active upper extremity position reproduction in overhead-throwing athletes at 2 functional positions, and (2) compare joint position sense acuity among planes of motion within each individual joint. We chose to observe reproduction acuity of 2 self-selected positions representing distinct components of the throwing motion, the arm-cock and ball-release positions. Because position sense is enhanced with the increased tension on static and dynamic stabilizers,^{21,22,31,32} we hypothesized that motions measured near midrange would display less acuity than those at end range. We hypothesized that (1) repositioning would be less accurate and more variable at the ball-release position than at arm cock, and (2) motions measured near midrange would display less accuracy and more variability than other motions within the same joint.

METHODS

Subjects

Subjects consisted of overhead-throwing athletes competing in National Collegiate Athletic Association Division I baseball.

Twenty-one male subjects (age = 20.8 ± 1.5 years, height = 181.3 ± 5.1 cm, mass = 87.8 ± 9.1 kg) volunteered for this study. Subjects reported baseball experience of 3.3 ± 1.3 years in Division I and 15.4 ± 1.9 total years. The athletes included 15 right-handed and 6 left-handed throwers, consisting of 4 pitchers, 9 infielders, and 8 outfielders. All testing took place during preseason conditioning. Participants had no history of upper extremity injury or central nervous system disorder. We gave instructions regarding the testing protocol, and participants signed an informed consent form. The University's Institutional Review Board for the Social and Behavioral Sciences approved this study.

Procedures

We used a single-session, repeated-measures design. We measured active multijoint position reproduction using the Flock of Birds electromagnetic tracking device (Ascension Technology Corp, Burlington, VT) with MotionMonitor software (Innovative Sports Training, Inc, Chicago, IL) collecting data at 100 Hz. This instrumentation is capable of tracking motion of multiple segments with 6 degrees of freedom. Subjects performed a 4- to 6-minute throwing warm-up before testing. We then palpated and marked standard anatomical landmarks³³ and attached the Flock of Birds sensors according to previously described and validated methods.³⁴ We attached sensors to each subject using double-backed tape or elastic cuffs. We taped sensors immediately distal to the sternal notch, on the dominant side at the posterior acromial angle of the scapula, and on the dorsal aspect of the third metacarpal. The sternal notch sensor functioned as a reference point during digitizing for each participant. Elastic, rubberized cuffs (2 in [5.08 cm] in width) and spray adhesive held additional sensors to the distal lateral humerus and the posterior aspect of the distal radius. The elastic cuffs also served to stabilize the cords from distal sensors to limit any sensor feedback from hanging cords. We digitized anatomical landmarks to create anatomically relevant coordinate systems for the thorax, scapula, humerus, forearm, and hand that would allow us to measure clinically meaningful joint rotations. Local coordinate systems and Euler rotations sequences used by MotionMonitor to calculate angular data followed the standardized protocol of the International Society of Biomechanics.³³

Active Multijoint Position Reproduction Measure

The active multijoint position reproduction measure assessed each subject's ability to recreate 2 upper extremity positions. During testing, subjects held a baseball in the throwing hand and kneeled in a standardized single-knee stance. We defined the position as the following: kneeling with the non-dominant hip flexed to 90° , foot placed flat on the ground in front of the subject, and the throwing shoulder-side knee on the ground. We instructed subjects to keep 90° angles at both knees. We chose this position to maintain a standard and appropriate distance between subjects and the electromagnetic transmitter. The manufacturer indicates that this system measures positional data accurately to 0.5° with a resolution of 0.1° at this distance (5 ft [1.52 m]). We established the reliability of our test measurements and procedures before beginning the study. We applied instruments to subjects and recorded 4 trials for each scapular motion and each additional upper extremity motion, repeatedly placing individual segments in

Reliability (Intraclass Correlation Coefficient) and Standard Error of Measure of Joint Position Sense Measures (°)

Joint Position	Intraclass Correlation Coefficient	Standard Error of Measure
Scapular upward rotation	0.85	1.01
Scapular internal rotation	0.90	0.76
Scapular posterior tilt	0.77	1.51
Glenohumeral flexion	0.95	0.63
Glenohumeral rotation	0.97	0.38
Elbow flexion	0.93	0.78
Forearm pronation	0.96	0.80
Wrist flexion	0.99	0.75

previously identified orientations. Intraclass correlation coefficients and standard errors of measure for each joint are presented in the Table.

We tested the subject's ability to reproduce 2 specific, self-determined positions that corresponded with 2 distinct moments of the throwing motion. For the first position, we asked subjects to hold their arm-cock position, described as the position at which forward acceleration of the arm would begin (Figure 1). We gave subjects a button to hold in the nonthrowing hand. Subjects pressed the button when they believed they had recreated the position. Before blindfolding subjects, we allowed them to practice the procedure 3 to 5 times, moving through the throwing motion, pausing, and indicating the positions. For the first recorded trial, investigators prompted subjects to go through the throwing motion, pause at the first position for approximately 1 second, and press the button. To ensure identification of each trial's position, the motion analysis system recorded 2.5 seconds of data both before and after depression of the trigger. We used a single frame corresponding with depression of the trigger to identify each position. Each subject's upper extremity position during this initial trial served as the target position for the 3 reposition trials to follow. We prompted subjects to begin each trial after a 5-second break, during which they remained blindfolded. Subjects completed all 3 reposition trials within 2 minutes of identifying the target position. We specifically instructed subjects to "recreate the position" so as to avoid creating bias toward any particular upper extremity segment or angle. Subjects then followed the same procedures for position 2. For the second position, we instructed subjects to identify and hold the ball-release position, described as the position of the arm when the ball is released (Figure 2). We did not give feedback to subjects regarding the acuity of individual trials at any time during the test.

Data Reduction and Statistical Analysis

We exported angular data into Microsoft Excel 2000 (Microsoft Corp, Redmond, WA) to calculate error scores and conducted statistical analyses using SPSS (version 10.0; SPSS Inc, Chicago, IL). We calculated position sense acuity for each joint and each plane of motion available: scapulothoracic (internal-external rotation, upward-downward rotation, posterior-anterior tilt) (Figure 3), glenohumeral (internal-external rotation [ie, long axis rotation], horizontal abduction-adduction [ie, plane of elevation], flexion-extension), elbow (pronation-supination, flexion-extension), and wrist (ulnar-radial deviation, flexion-extension). Researchers have indicated that taking only

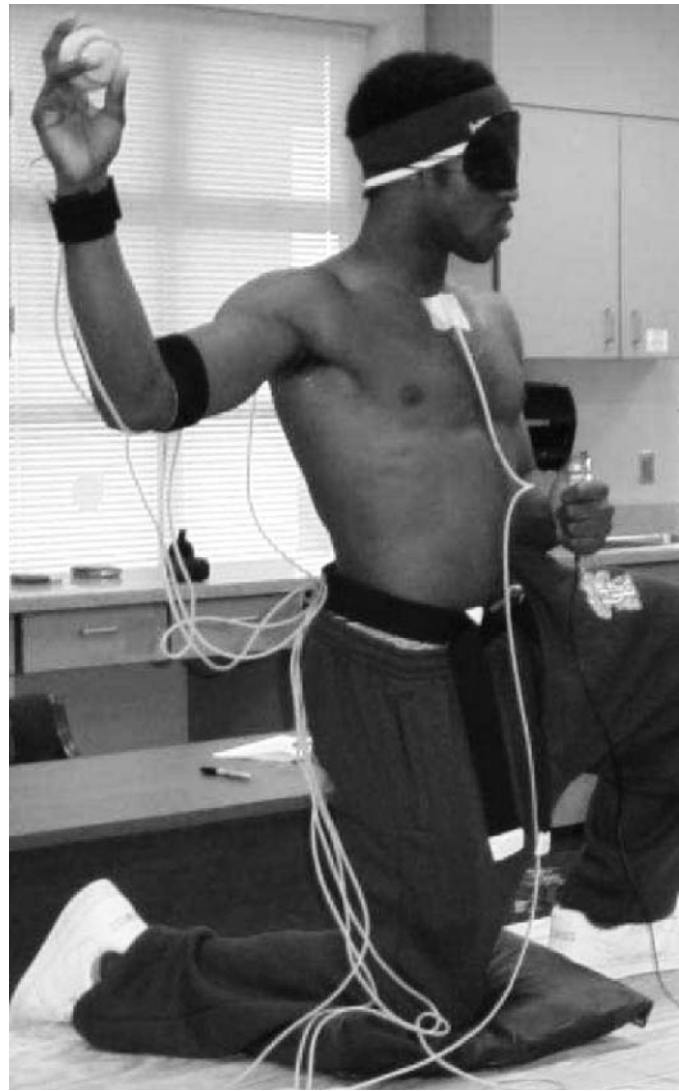


Figure 1. An overhead-throwing athlete identifying his arm-cock position, the first of 2 subject-selected positions tested.

1 measure of reposition is insufficient.^{10,35,36} Therefore, we calculated absolute error (AE) and variable error (VE) using the differences between the target and repositioned angle for each plane of motion and each of the 3 trials.

Absolute error describes the magnitude of repositioned error and is used to represent overall accuracy.^{35,37} We averaged the absolute value of errors over the 3 trials using the following equation:

$$\text{Absolute Error} = \sum |X_{\text{trial}_i} - X_{\text{target}}|/n$$

where X_{trial_i} and X_{target} are defined as the angle of trial i and target angle, respectively, and n is the number of trials (3).

Variable error scores represent subjects' consistency or variability in repositioning trials. These VE scores do not reflect reposition accuracy but indicate the amount of deviation among trials.³⁵⁻³⁷ Researchers suggest that these 2 measures (AE and VE) constitute a thorough investigation of joint position sense acuity.³⁵ We calculated VE using the following equation:

$$\text{Variable Error} = \sqrt{\sum (X_{\text{trial}_i} - X_{\text{mean}})^2/n}$$



Figure 2. An overhead-throwing athlete identifying his ball-release position, the second of 2 subject-selected positions tested.

where X_{trial_i} and X_{mean} are defined as the angle of trial i and mean of trials, respectively, and n is the number of trials (3).

We calculated the overall position sense acuity for each joint. Three-dimensional variable error scores (3DVE) reflect acuity (measured in degrees) in all planes of motion measured for individual joints. We calculated 3DVE as a global standard deviation of end-position dispersions³⁸ using the following equation:

$$\begin{aligned} \text{3D Variable Error} \\ = \sqrt{[SD_x(D_x)]^2 + [SD_y(D_y)]^2 + [SD_z(D_z)]^2} \end{aligned}$$

where D_x , D_y , and D_z are sums of the constant error between target and trial angles around the x, y, and z axes, and the SDs are their respective standard deviations.

Because 81% of all variables (39 of 48) violated the assumption of normality (either Kolmogorov-Smirnov or Shapiro-Wilk test), nonparametric tests were appropriate. For each measure of acuity (AE, VE, and 3DVE), we performed a Kruskal-Wallis test (nonparametric 1-way analysis of variance) to

examine differences between the arm-cock and ball-release positions. We used additional Kruskal-Wallis tests to compare error scores among planes of motion within each individual joint. We set the statistical significance for all comparisons at $P < .05$ a priori and used the Dunn correction for multiple comparisons when appropriate.

RESULTS

Comparison of Arm-Cock to Ball-Release Position

Our primary purpose for this study was to compare active upper extremity position reproduction of overhead-throwing athletes at 2 positions, arm cock and ball release.

Absolute Error. We observed significantly less accuracy (greater AE scores) for ball release than arm cock in (1) scapulothoracic internal-external rotation (4.2° and 1.5°) ($\chi^2 = 22.485$, $P < .001$), (2) glenohumeral horizontal abduction-adduction (4.2° and 2.0°) ($\chi^2 = 10.126$, $P = .003$), and (3) glenohumeral rotation (5.0° and 2.6°) ($\chi^2 = 7.588$, $P = .018$; Figure 4). No significant differences were noted in accuracy at arm cock when compared with ball release at the elbow or wrist ($P > .05$).

Variable Error. We observed significantly greater variability at ball release than arm cock in (1) scapulothoracic internal-external rotation (2.2° and 0.8°) ($\chi^2 = 13.397$, $P < .001$), (2) glenohumeral horizontal abduction-adduction (2.7° and 1.1°) ($\chi^2 = 9.189$, $P = .006$), and (3) glenohumeral rotation (3.0° and 1.4°) ($\chi^2 = 8.442$, $P = .012$; Figure 5). No significant differences were seen between variability at arm cock when compared to ball release at the elbow or wrist ($P > .05$).

3-Dimensional Variable Error. We observed significantly greater 3DVE scores at ball release compared to arm cock at the following joints: (1) scapulothoracic (12.5° and 5.5°) ($\chi^2 = 6.648$, $P = .03$) and (2) glenohumeral (19.1° and 8.2°) ($\chi^2 = 6.91$, $P = .027$; Figure 6). There were no significant differences between 3DVE scores at arm cock and scores in any planes of motion at any of the joints ($P > .05$).

Comparisons Among Planes of Motion Within Individual Joints

Absolute Error. At arm cock, no significant differences were noted among accuracy scores in any planes of motion at any joint ($P > .05$). At ball release, we found less accuracy in scapulothoracic internal rotation (4.1°) than in posterior tilt (2.5°) and upward rotation (2.2°) ($P = .003$) and less accuracy in glenohumeral horizontal abduction (4.2°) and rotation (5.0°) than in flexion (2.1°) ($P = .006$). No significant differences were seen in accuracy measured at the 3 planes of motion for the elbow or wrist joints ($P > .05$) for ball release.

Variable Error. At arm cock, no significant differences were demonstrated in any planes of motion at any joint ($P > .05$). At ball release, significant differences were noted, with greater variability in scapulothoracic internal rotation (2.2°) than in posterior tilt (1.3°) or upward rotation (1.2°) ($P = .03$) and in glenohumeral horizontal abduction (2.8°) and rotation (2.9°) than in flexion (1.2°) ($P = .015$). No significant differences were shown in variability among the plane of motion at the elbow or wrist joints ($P > .05$).

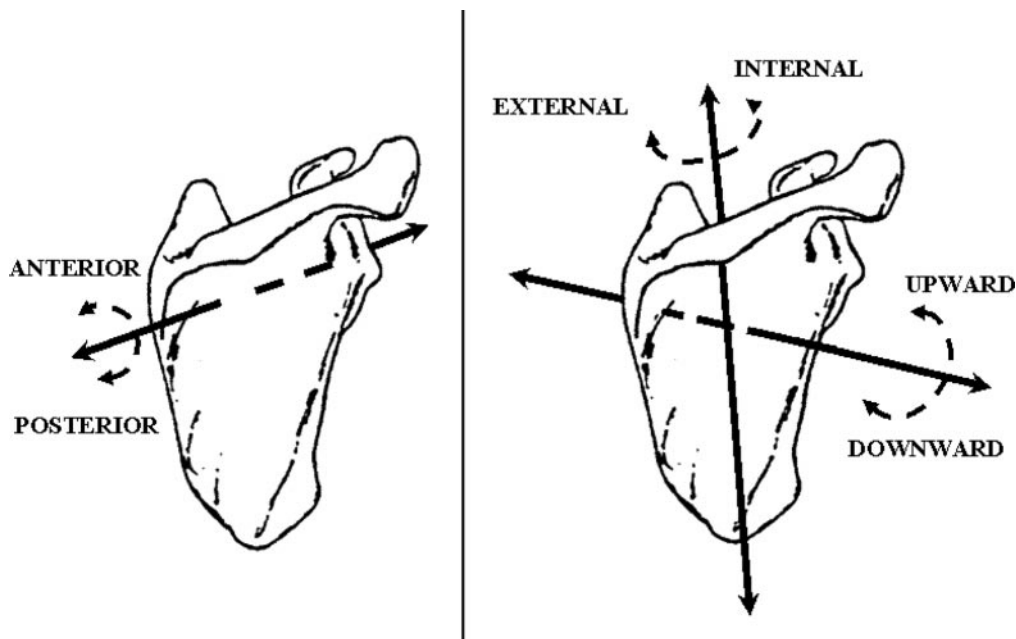


Figure 3. Scapular axes and motions: anterior-posterior tilt, internal-external rotation, and upward-downward rotation.

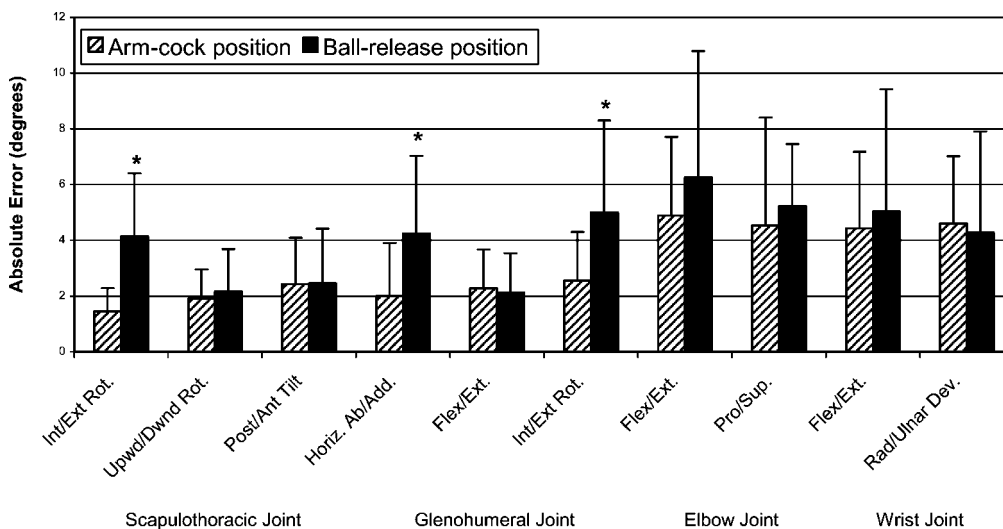


Figure 4. Absolute error score means ($^{\circ}$) for the scapulothoracic, glenohumeral, elbow, and wrist joints at the arm-cock and ball-release positions. *Indicates significantly better acuity (less error) observed at the arm-cock position than the ball-release position ($P < .05$). Int/Ext Rot. indicates internal-external rotation; Upwd/Dwnd Rot., upward-downward rotation; Post/Ant Tilt, posterior-anterior tilt; Horiz. Ab/Add., horizontal abduction-adduction; Flex/Ext., flexion-extension; Pro/Sup., pronation-supination; Rad/Ulnar Dev., radial-ulnar deviation.

DISCUSSION

The purposes of this paper were to (1) describe and compare active upper extremity position reproduction of overhead-throwing athletes at 2 functional positions, and (2) compare joint position sense acuity among individual planes of motion within each joint. Before addressing each purpose individually, it is important to consider how our data compare with the data of others.

The AE we observed at the scapulothoracic joint was 1.5° to 2.4° at arm cock and 2.2° to 4.1° at ball release. Because our joint position sense measures at the scapulothoracic joint were unique, we were unable to compare these results with

previous observations. We should note, however, that the glenohumeral joint displayed similar ranges of accuracy: 2.0° to 2.6° at arm cock and 2.1° to 5.0° at ball release. Our subjects' accuracy for glenohumeral rotation was 2.6° at arm cock and 5.0° at ball release, which is comparable with the 3.8° and 5.0° for internal and external rotation, respectively, observed in softball players.²⁴ The accuracy of glenohumeral flexion we observed (2.1° to 2.3°) was comparable with that reported for uninjured groups (2.5°)³⁹ and softball players (3.7° and 3.5°).²⁴ Our results also indicate that variability is similar between the scapulothoracic and glenohumeral joints at both positions tested. The observation of such errors at the scapulothoracic joint,

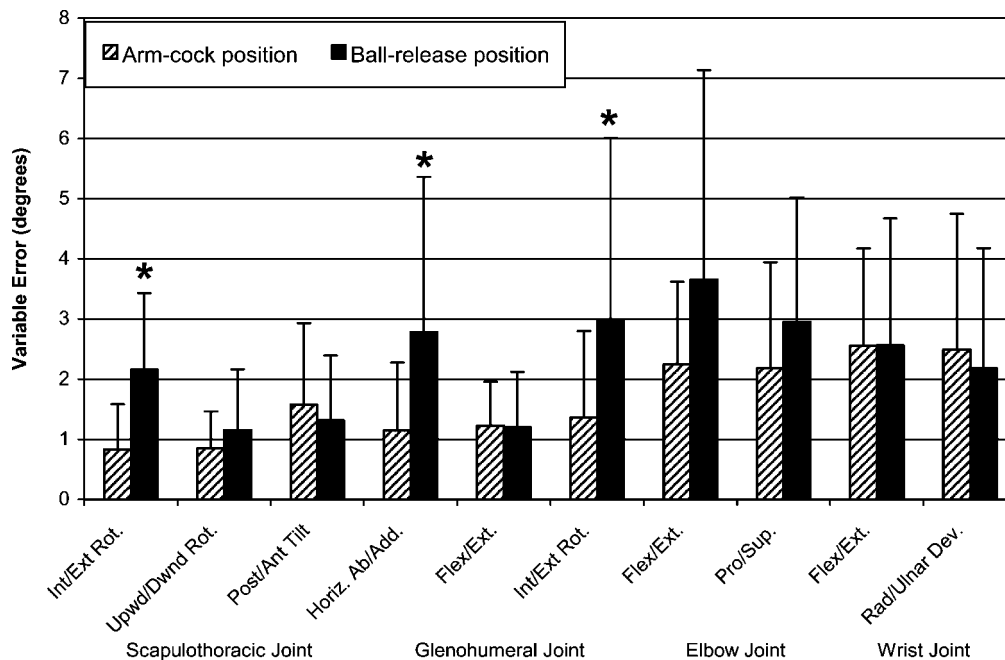


Figure 5. Variable error score means (°) for the scapulothoracic, glenohumeral, elbow, and wrist joints at the arm-cock and ball-release positions. *Indicates significantly better acuity (less error) observed at the arm-cock position than the ball-release position ($P < .05$). Int/Ext Rot. indicates internal-external rotation; Upwd/Dwnd Rot., upward-downward rotation; Post/Ant Tilt, posterior-anterior tilt; Horiz. Ab/Add., horizontal abduction-adduction; Flex/Ext., flexion-extension; Pro/Sup., pronation-supination; Rad/Ulnar Dev., radial-ulnar deviation.

however, is unappreciated in research that focuses only on the glenohumeral joint.^{5,19,21–26,40–42} The range of variability (2.2° to 3.7°) and accuracy (4.5° to 6.3°) we observed for elbow flexion was similar to results of previous single-plane measures.³²

Differences Between Positions

Our results indicate that overhead-throwing athletes are both less accurate and more variable in reproducing scapulothoracic and glenohumeral joint positions at ball release than at arm cock. These data support previous reports that positions in the midrange of motion^{21,22,31,32} are less accurate than positions toward the end range. In the arm-cock position, the abduction and external rotation cause significant tightening of the glenohumeral joint capsule.^{22,43} Therefore, our results provide evidence corroborating the theory that increased tension in joint capsules and muscles increases afferent feedback and subsequent joint position sense acuity.^{21,22,31,44} The implication of these results is that clinicians can place further emphasis on incorporating functional positions throughout the range of motion in protocols targeting the SMS.

Differences Among Planes of Motion Within Each Joint

We did not observe any significant within-joint differences in the accuracy or variability occurring in any of the planes of motion at arm cock. Although past investigators have not made direct comparisons of this type, rotation is believed to display the most variability of glenohumeral motions.⁴⁵ Our results indicate that glenohumeral rotation is more variable than flexion but not horizontal abduction. At ball release, the scapulothoracic joint displayed less accuracy and more vari-

ability in internal-external rotation than the other 2 scapular motions. Although this finding was statistically significant, we may question the clinical significance of 1° to 3° differences. However, when we consider these differences in the functional context, along with deficiencies observed in related motions, the clinical implications become clear. Deficits in scapular internal-external rotation, coupled with those at the glenohumeral joint, may provide insight into the mechanisms of shoulder injuries such as posterior internal impingement. We observed significant deficits in variability and accuracy for glenohumeral horizontal abduction and rotation. These results may be a byproduct of the excessive glenohumeral motion in both of these planes, changes that have been related to anterior laxity or posterior contracture caused by the repetitive stresses of throwing.^{2,46} This laxity, along with decreased acuity in the horizontal plane for both the glenohumeral and scapulothoracic joints, may compromise the limited arch of stability afforded by the glenohumeral articulation.^{46–48} Functional instability in this plane, particularly when coupled with glenohumeral rotation, is identified as a primary cause of posterior internal impingement in throwers.^{46,47} Certainly further research must be conducted, including a focus on dynamic motions, but our results indicate that scapulothoracic error must be considered one potential source of symptoms.

Limitations

Our results are limited to Division I baseball players with no injury or history of major upper extremity surgery. Results may vary among populations and activity levels. Additionally, we did not standardize test positions among subjects. Thus, we recognize that they may not be exact representations of each individual's arm-cock and ball-release positions. We measured reproduction of self-selected positions familiar to the

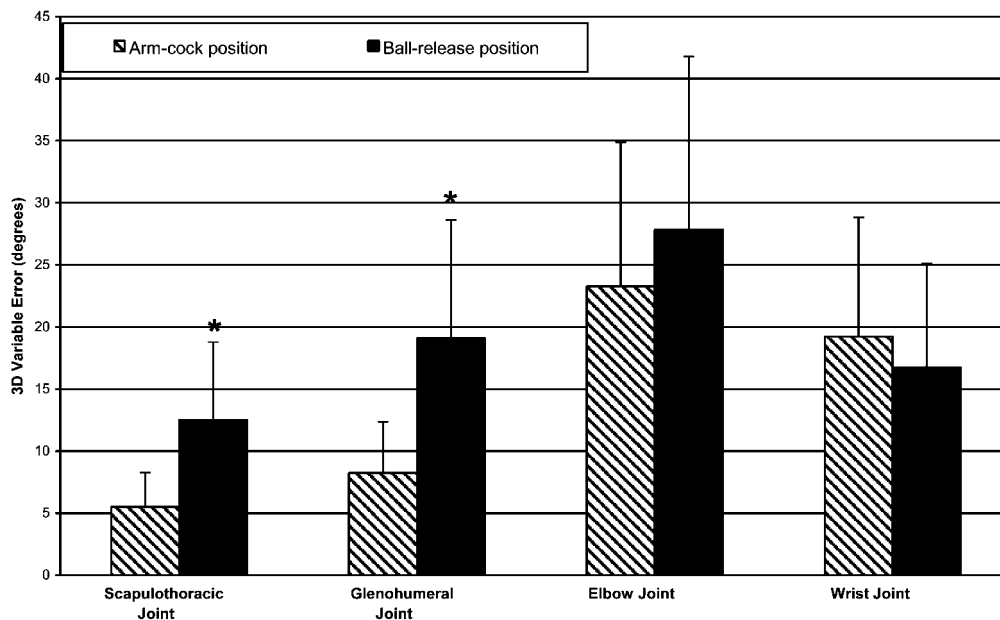


Figure 6. 3D variable error score means (°) for the scapulothoracic, glenohumeral, elbow, and wrist joints at the arm-cock and ball-release positions. *Indicates significantly better acuity (less error) observed at the arm-cock position than at the ball-release position ($P < .05$).

population and feel that replication of predetermined positions is too constraining for a highly dynamic system, severely limiting our insight into multiple planes of motion.

Future Research

Future researchers should observe the effects of various conditions (injury, fatigue) on active multijoint position reproduction acuity. Additionally, future investigators should examine differences among populations (age, activity level).

CONCLUSIONS

We developed a reliable, multijoint, 3-dimensional measure to assess joint position sense in Division I baseball players. We observed that position of the upper extremity affected SMS acuity. Subjects displayed better acuity at the glenohumeral and scapulothoracic joints in the arm-cock position than in ball release. Our results also indicate differences in variability and accuracy among planes of motion in the glenohumeral and scapulothoracic joints. Scapulothoracic internal rotation and glenohumeral horizontal abduction and rotation displayed less acuity than other motions. Clinicians should consider these differences when designing and implementing SMS training protocols. Understanding that the position of the upper extremity affects acuity and that differences exist among planes of motion, clinicians may consider employing exercises that address multiple positions, joints, and planes of motion. The error scores we observed are similar in magnitude to those reported using single-plane and single-joint methods. However, 3-dimensional, multijoint measures allow practical, unconstrained test positions and offer additional insight into the upper extremity as a functional unit.

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