

The Influence of External Loads on Movement Precision During Active Shoulder Internal Rotation Movements as Measured by 3 Indices of Accuracy

Timothy J. Brindle*; Timothy L. Uhl†; Arthur J. Nitz†; Robert Shapiro†

*National Institutes of Health, Bethesda, MD; †University of Kentucky, Lexington, KY

Timothy J. Brindle, PhD, ATC, PT, contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article. Timothy L. Uhl, PhD, ATC, PT; Arthur J. Nitz, PhD, PT; and Robert Shapiro, PhD, FACSM, contributed to conception and design, analysis and interpretation of the data, and critical revision and final approval of the article.

Address correspondence to Timothy J. Brindle, PhD, ATC, PT, Physical Disabilities Branch, National Institutes of Health, Building 10 CRC, Room 1-1469 MCS 1604, Bethesda, MD 20892-1604. Address e-mail to tbrindle@cc.nih.gov.

A collaboration between the National Institute of Child Health and Human Development and the Mark O. Hatfield Clinical Research Center, National Institutes of Health.

Context: Using constant, variable, and absolute error to measure movement accuracy might provide a more complete description of joint position sense than any of these values alone.

Objective: To determine the effect of loaded movements and type of feedback on shoulder joint position sense and movement velocity.

Design: Applied study with repeated measures comparing type of feedback and the presence of a load.

Setting: Laboratory.

Patients or Other Participants: Twenty healthy subjects (age = 27.2 ± 3.3 years, height = 173.2 ± 18.1 cm, mass = 70.8 ± 14.5 kg) were seated with their arms in a custom shoulder wheel.

Intervention(s): Subjects internally rotated 27° in the plane of the scapula, with either visual feedback provided by a video monitor or proprioceptive feedback provided by prior passive positioning, to a target at 48° of external rotation. Subjects performed the internal rotation movements with video feedback

and proprioceptive feedback and with and without load (5% of body weight).

Main Outcome Measure(s): High-speed motion analysis recorded peak rotational velocity and accuracy. Constant, variable, and absolute error for joint position sense was calculated from the final position.

Results: Unloaded movements demonstrated significantly greater variable error than for loaded movements ($2.0 \pm 0.7^\circ$ and $1.5 \pm 0.4^\circ$, respectively) ($P < .05$), but there were no differences in constant or absolute error. Peak velocity was greater for movements with proprioceptive feedback ($45.6 \pm 2.9^\circ/\text{s}$) than visual feedback ($39.1 \pm 2.1^\circ/\text{s}$) and for unloaded ($47.8 \pm 3.6^\circ/\text{s}$) than loaded ($36.9 \pm 1.0^\circ/\text{s}$) movements ($P < .05$).

Conclusions: Shoulder joint position sense demonstrated greater variable error unloaded versus loaded movements. Both visual feedback and additional loads decreased peak rotational velocity.

Key Words: proprioception, kinesthesia, shoulder function

Investigators researching shoulder proprioception typically evaluate either joint position sense (JPS), the ability to replicate a fixed target, or kinesthesia, the ability to detect onset of passive motion.^{1,2} Evaluating JPS involves either active or passive reproduction of a previously presented position or target. Passive movement toward the target is measured to diminish the influence of the gamma motor system on muscle spindles, whereas active movements are more representative of human movements.³ Active and passive tests of JPS have not shown significant differences.⁴ Mechanoreceptors from cutaneous, articular, and musculotendinous regions, in addition

to visual feedback (VF), can influence movement accuracy because the central nervous system (CNS) integrates all of this feedback.⁵ When vision is obscured, the CNS can maintain movement accuracy to some degree through proprioceptive feedback (PF) alone. Although movements without vision are clearly less accurate, how PF influences performance is unknown. However, the contribution of PF to maintaining function is believed to be fairly substantial.^{6,7} It is also difficult to determine the influence of each of these receptors (musculotendinous, articular, and cutaneous) on proprioceptive ability.

Three types of muscle receptors contribute to joint proprioception: static and dynamic muscle spindles and Golgi tendon organs (GTOs), in which muscle spindles play the dominant role.^{8–10} Joint receptors play a greater role near the end range of a joint, whereas cutaneous receptors contribute more position sense in the hand than in other joints.^{10–14} Muscle spin-

The opinions presented in this report reflect the views of the authors and not those of the National Institutes of Health or the US Public Health Service.

dles lie in parallel with extrafusal muscle fibers and provide proprioceptive feedback regarding muscle length and change in length (velocity).^{9,10} Spindles are also involved with the monosynaptic stretch reflex.⁸ However, the GTO lies in series with extrafusal muscle fibers near the musculotendinous junction and provides feedback of force within the muscle tendon complex.¹⁵ The GTO is more sensitive to forces generated with active movement than with passive stretching of the muscle-tendon complex.^{16,17} The GTO responds to active tension within a muscle-tendon complex and may influence JPS during loaded movements.⁸

Although muscle spindle afferents (Ia and II) provide a direct connection to the alpha motor neuron in the spinal cord, only indirect connections exist between GTO afferents (Ib) and the alpha motor neuron. Instead, a wide array of connections serve the muscle of afferent origin via interneurons in the spinal cord to the alpha motor neuron but also neurons affecting synergists and antagonist muscles and higher centers of the CNS.⁸ These interneurons make it difficult to determine the exact role of the GTO in movement control. It was originally believed¹⁵ that the GTO provided only autogenic inhibition or self-inhibition during maximal muscle activation to prevent muscular injury. However, autogenic inhibition from the GTO is relatively weak, compared with feedback from spindle afferents and GTOs, and it is also more responsive at submaximal levels of muscle activation.⁸ Interneurons that receive feedback from the GTO also receive afferent feedback from joint and cutaneous receptors, which appear to enhance the inhibition from the GTO.¹⁸ This type of peripheral feedback is thought to prevent the use of excessive force to overcome potentially immovable objects that can be encountered during voluntary movements.^{8,18} The role of the GTO in JPS and kinesthesia is unclear and in need of further study.

Shoulder JPS is reported as performance, or movement accuracy, in terms of “average mean difference error” or constant error (CE) of angular position of a rotated humerus with respect to a previously described fixed angular position. Other measures of accuracy or consistency include variable error (VE) and absolute error (AE). Calculations of these measures are provided in the Methods section. Absolute error might be a more sensitive method of measuring accuracy than CE; however, CE gives an indication of the direction error, whereas VE provides information regarding consistency of a performance.^{19,20} Consistently overshooting a target generates a small VE and larger CE and AE values. Conversely, a high degree of inconsistency (VE) can also be generated with small CE scores: inconsistent accuracy. Using all 3 measures of performance could provide a more complete description of performance based on overall accuracy (AE), a measure of the direction of the error (CE), and the variability of the performance (VE).

Our main purpose was to determine the effect of external loads on movement accuracy and movement velocity with VF and PF or proprioceptive feedback alone. A secondary purpose of this study was to determine if differences in performance between loaded and unloaded movements can be determined with measures such as CE, VE, and AE.

METHODS

Subjects

Twenty subjects, with equal numbers of males and females (age = 27.2 ± 3.3 years, height = 173.2 ± 18.1 cm, mass =

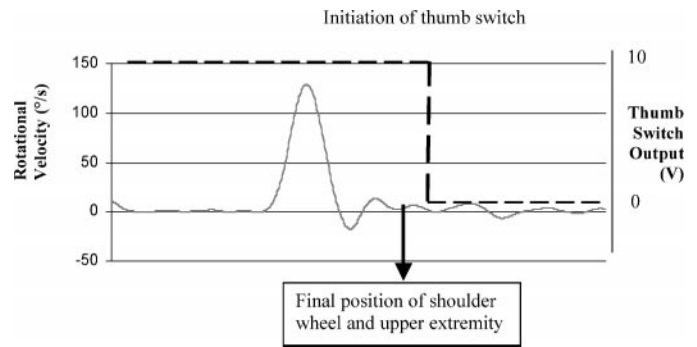


Figure 1. Final position for upper extremity was determined when angular velocity ($^{\circ}/s$) of the shoulder wheel was nearest zero before the thumb switch was activated (9 V).

70.8 ± 14.5 kg) were recruited from the general student population. Subjects were screened by a certified athletic trainer with a brief medical history and assessment of glenohumeral range of motion (internal and external rotation), upper extremity muscle strength, and upper quarter sensation.²¹ We used these tests to exclude individuals with a history of shoulder injury, such as glenohumeral dislocation or chronic subluxation, or any injury that could result in neurovascular compromise to the dominant upper extremity. All subjects provided informed written consent. The institutional review board reviewed and approved the protocol for this study.

The subjects’ dominant upper extremity, defined as the extremity with which they preferred to throw, was tested. All subjects were right-hand dominant. Subjects’ internal and external ranges of motion for the right glenohumeral joint were $51.7 \pm 15.2^{\circ}$ and $87.5 \pm 13.7^{\circ}$, respectively.

Instrumentation

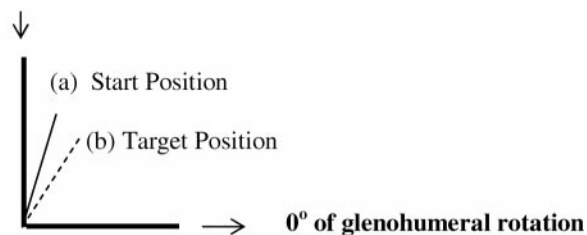
Data Acquisition: Video Capture System. Kinematic data were recorded by 3 high-speed Falcon Cameras (Motion Analysis Corp, Santa Rosa, CA) positioned around the shoulder wheel, approximately 5 m away and elevated approximately 4 m above the floor. Data were collected at a sampling rate of 240 Hz. Spatial, 3-dimensional coordinate data for the 3 retroreflective markers were determined using the direct linear transformation²² as modified with Motion Analysis software. Coordinate data were smoothed with a 4th-order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 6 Hz.²³ We used standard trigonometry to calculate the angle formed by the stationary arm and the movable arm of the shoulder wheel (EVA software, Motion Analysis Corp). Angular displacement of the movable arm of the shoulder wheel relative to the stationary arm enabled approximation of the instantaneous angular position for shoulder wheel internal rotation. The instantaneous angular velocity for shoulder internal rotation movement was calculated using central differences.²³

Thumb Switch. The subjects activated a thumb switch, connected to a 9-V battery, to indicate when they thought they had reached the target position. The analog signal from the thumb switch (collected at 960 Hz) was synchronized with the motion capture system. The final location of the movable arm of the shoulder wheel, representing the subject’s ability to replicate the target, was defined as the angular position of the wheel when instantaneous angular velocity of the wheel was nearest zero before activating the thumb switch (Figure 1).



A.

90° glenohumeral external rotation



B.

Figure 2. A, Subject seated with upper extremity positioned in plane of scapula (30° horizontally adducted from the coronal plane) with arm abducted to 90° and externally rotated in the starting position. Retroreflective markers (1, 2, and 3) on shoulder wheel enable the calculation of peak internal rotation velocity and final position. A shield (*) prevented the use of peripheral vision and direct visualization of the arm during testing. Loaded trials included the use of an external weight (†) attached to the shoulder wheel. B, Subjects start from the position of 75° of external rotation (a) and internally rotate 27° to the target position at 48° of external rotation (b).

Testing Procedures

Shoulder Wheel Apparatus. A custom shoulder wheel, used in previous studies, was employed for this investigation^{24,25} (Figure 2A). The movable arm of the shoulder wheel was padded with foam to distribute pressure evenly throughout the forearm in order to minimize cutaneous feedback, which can influence PF.^{26,27}

The shoulder wheel was instrumented with 3 retroreflective markers, allowing the video capture system to determine its position and velocity. Marker 1 was attached on the vertical stationary arm and aligned with the axis of rotation of the shoulder wheel. Marker 2 was located on the stationary arm, directly vertical to marker 1. Marker 3 was placed on the movable arm of the shoulder wheel, approximating the subject's hand location (see Figure 2A). The positioning and orientation of the shoulder wheel device, in conjunction with fixation of the forearm in the compression sleeve, served to align the shoulder wheel axis with the glenohumeral joint and to maintain the shoulder in the scapular plane during data collection.

This enabled the shoulder wheel movable arm to provide an estimate of glenohumeral motion.^{1,2,4,25,28,29}

Buttresses attached to the rim of the shoulder wheel limited range of motion from 75° (starting position of external rotation) to 0°, or neutral, in order to prevent injury. The buttress that limited external rotation also provided a consistent starting position for all subjects. A movable third buttress was used to consistently place each subject's shoulder at the target position of 48° of external rotation, or 27° from the starting position. The buttress was moved out of the way as required during data collection trials. The angular displacement in this study was similar to that in previous shoulder proprioception studies.^{1,2,28} Moreover, this position is an attempt to replicate arm position during throwing, which has been used in previous studies of shoulder proprioception and can have an effect on accuracy of performance (ie, throwing).^{25,30}

Constant error, or CE, is calculated as follows:

$$CE = \frac{\sum (x_i - T)}{n}$$

where x_i is the individual trial, T is the target, and n is the number of trials. Other measures of movement accuracy include VE and AE and are calculated as follows:

$$VE = \sqrt{\frac{\sum (x_i - \bar{X})^2}{n}}, \quad AE = \frac{\sum |x_i - T|}{n}$$

where x_i is the individual trial, \bar{X} is the mean of the trials collected, T is the target position, and n is the number of trials collected.

Subject Position. Subjects sat upright with the arm and shoulder in the plane of the scapula and the shoulder abducted and horizontally adducted to 90° and 30°, respectively.³¹ The elbow was flexed to 90° with the forearm in a neutral position. The forearm was inserted into a custom-made shoulder wheel and stabilized by a compressive sleeve around the forearm (see Figure 2A). The glenohumeral joint axis of rotation was visually aligned with the axis of rotation of the shoulder wheel. Subjects wore goggles with a shield to block peripheral vision and to prevent direct visualization of the arm, forearm, hand, and shoulder wheel during all trials.

Proprioceptive Feedback

Subjects were passively moved from the starting position to the target position, approximating the movable buttress that was put into place, and held in that position for 10 seconds. They were instructed that this was the target position they were to replicate, thus providing them with the proprioceptive information needed to identify the target location. Subjects were passively returned to the starting position before the beginning of active replication of the target position. The movable buttress was removed from the intended path of motion, so it would not interfere if motion exceeded the 27° of rotation.

Visual Feedback

Subjects were provided VF by monitor connected to a fourth video camera, independent of the motion analysis system, which enabled them to judge movement accuracy. The camera was located 3 m from the shoulder wheel apparatus, oriented with its lens-to-object axis parallel to the rotational axis of the shoulder wheel. The video monitor (38.1 cm di-

Table 1. Constant Error of Movements With and Without a Load and Visual Feedback (°) (Mean ± SD)

	Visual Feedback	Proprioceptive Feedback	Main Effects (Loaded versus unloaded)
Unloaded	-0.2 ± 0.5	3.7 ± 4.0	1.8 ± 2.4
Loaded	-0.1 ± 0.6	3.9 ± 3.9	1.9 ± 3.5
Main Effect (Visual feedback versus proprioceptive feedback)	-0.1 ± 0.6*	8 ± 3.9	

*Indicates significant difference between movements with visual and proprioceptive feedback ($P < 0.05$).

Table 2. Variable Error of Movements With and Without a Load and Visual Feedback (°) (Mean ± SD)

	Visual Feedback	Proprioceptive Feedback	Main Effects (Loaded versus unloaded)
Unloaded	0.9 ± 0.5	3.1 ± 1.3	2.0 ± 0.7
Loaded	0.6 ± 0.2	2.5 ± 0.8	1.5 ± 0.4†
Main Effect (Visual feedback versus proprioceptive feedback)	0.7 ± 0.4*	2.8 ± 0.2	

*Indicates significant difference between movements with visual and proprioceptive feedback ($P < 0.05$).

†Indicates significant difference between unloaded and loaded movements ($P < 0.05$).

Table 3. Absolute Error of Movements With and Without a Load and Visual Feedback (°) (Mean ± SD)

	Visual Feedback	Proprioceptive Feedback	Main Effects (Loaded versus unloaded)
Unloaded	0.4 ± 0.3	4.6 ± 3.2	2.5 ± 3.1
Loaded	0.5 ± 0.5	4.6 ± 3.4	2.5 ± 3.2
Main Effect (Visual feedback versus proprioceptive feedback)	0.5 ± 0.4*	4.6 ± 3.3	

*Indicates significant difference between movements with visual and proprioceptive feedback ($P < 0.05$).

agonal) for this separate camera was placed 2 m away from the subject in the frontal plane to provide real-time 2-dimensional VF of the retroreflective markers of the shoulder wheel and target during the VF condition. The video monitor was covered during the PF condition to eliminate the VF of the retroreflective markers and targets.

Protocol

Subjects performed JPS testing with and without an external load, defined as 5% body weight, in both the VF and PF conditions (see Figure 2A). Subjects were required to internally rotate 27° (75° of external rotation to 48° of external rotation) in order to replicate the fixed target (Figure 2B). Subjects were

Table 4. Peak Rotational Velocity of Movements With and Without a Load and Visual Feedback (°) (Mean ± SD)

	Visual Feedback	Proprioceptive Feedback	Main Effects (Loaded versus unloaded)
Unloaded	43.4 ± 3.1	52.1 ± 4.9	47.8 ± 3.6
Loaded	34.7 ± 1.3	38.9 ± 1.1	36.9 ± 1.0†
Main Effect (Visual feedback versus proprioceptive feedback)	39.1 ± 2.0*	45.6 ± 2.9	

*Indicates significant difference between movements with visual and proprioceptive feedback ($P < 0.05$).

†Indicates significant difference between unloaded and loaded movements ($P < 0.05$).

instructed to move at a comfortable speed for all 4 movement conditions (VF loaded, VF unloaded, PF loaded, and PF unloaded). A total of 32 trials were performed by each subject. Each trial was randomly assigned, in a nonrepeating, counter-balanced fashion, to each of the 4 movement conditions, generating 8 trials per condition. This final arm and shoulder wheel apparatus position enabled the calculation of movement accuracy measures relative to the target position (CE, VE, and AE). We calculated the mean of the 8 trials for each of the 4 movement conditions and used that value for statistical analysis. Breaks were typically provided after blocks of 10 to 20 repetitions, or on the subject's request, and lasted 5 to 10 minutes. These frequent breaks were allowed to minimize the influence of muscular and mental fatigue. This procedure took approximately 1.5 hours to complete, as it was part of a larger study that included other movement conditions.²⁴

Statistical Analysis

We calculated peak angular velocity of the movable arm of the shoulder wheel for all 4 movement conditions. Independent variables were the type of feedback (PF, VF) and presence or absence of the load (unloaded, loaded). Dependent variables included CE, VE, AE, and peak angular velocity.

Separate 2 × 2 fully repeated analyses of variance were performed to evaluate the effects of feedback and load on the CE, VE, AE, and peak angular velocity (version 11.5; SPSS Inc, Chicago, IL). The level of significance for each test was $P < .05$.

RESULTS

No significant interactions were noted between the 2 main conditions (type of feedback and the presence of a load) for CE ($F_{1,19} = 0.22$, $P = .698$, $1 - \beta = .066$), VE ($F_{1,19} = 1.21$, $P = .268$, $1 - \beta = .181$), or AE ($F_{1,19} = 0.009$, $P = .925$, $1 - \beta = .051$) (Tables 1–3). Moreover, we found no significant interactions between the type of feedback and the presence of a load on peak angular velocity ($F_{1,19} = 23.7$, $P = .421$, $1 - \beta = .12$) (Table 4).

No significant differences were seen between the main effect of loaded and unloaded movement accuracy as measured by CE ($F_{1,19} = 0.27$, $P = .61$, $1 - \beta = .08$) and AE ($F_{1,19} = 0.007$, $P = .94$, $1 - \beta = .05$) (see Tables 1 and 3). However, unloaded movements demonstrated significantly greater VE ($F_{1,19} = 11.5$, $P = .003$, $1 - \beta = .886$) than loaded

movements, signifying less consistency associated with these movements (see Table 2).

Movements were much less accurate and consistent in the PF than the VF condition; significant differences were demonstrated in CE ($F_{1,19} = 23.7, P < .001, 1 - \beta = 1.0$), VE ($F_{1,19} = 82.6, P < .001, 1 - \beta = 1.0$), and AE ($F_{1,19} = 35.9, P < .001, 1 - \beta = 1.0$) (see Tables 1–3).

Unloaded movements demonstrated greater ($F_{1,19} = 13.7, P = .003, 1 - \beta = .91$) peak rotational velocity ($47.8 \pm 8.3^\circ/s$) than the loaded condition ($36.9 \pm 4.2^\circ/s$). Movements for the PF condition demonstrated greater ($F_{1,19} = 4.9, P = .04, 1 - \beta = .55$) peak rotational velocity ($45.6 \pm 7.3^\circ/s$) than the VF ($39.1 \pm 5.7^\circ/s$) condition (see Table 4).

DISCUSSION

Our purpose was to examine the influence of an added external load on movement velocity, accuracy, and consistency in movements that used primarily VF and movements that used primarily PF. Performance error was quantified by 3 measures (CE, VE, and AE,) and peak rotation velocity was recorded for each movement. Although our main focus was not the difference between the VF and PF conditions, we include this comparison to examine the influence of added loads during JPS testing and movements with visual feedback.

Force sensation and position sense have been reported to be inextricably linked, suggesting a role for the GTO and muscle spindles during functional movements.^{32,33} After the target position was established with passive positioning, active movement was used to replicate the target in an effort to maximize the GTO influence on JPS, as the GTO operates more effectively with submaximal muscle activation.^{8,16,17} Light loads were also used in an effort to avoid fatigue. The presence of a load during PF movements, similar to JPS testing, had no significant effect on accuracy measured with CE and AE. Loaded movements demonstrated lower VE scores than unloaded movements ($1.5 \pm 0.4^\circ$ and $2.0 \pm 0.4^\circ$, respectively), indicating greater consistency in the ability of subjects to replicate the target. Added weight during PF movements was used to enhance GTO feedback during active movements during the study of shoulder JPS. Additional loads have been used to demonstrate enhanced elbow JPS.³⁴ However, we are unable to directly compare our results with those of previous shoulder investigations, as there appear to be no other published studies on how additional loads affect shoulder JPS.

Another possible reason for the lack of a significant difference in accuracy as measured by CE and AE between the loaded and unloaded conditions could be the minimal influence of GTO feedback on human movement control compared with the influence of muscle spindle feedback.⁸ Additionally, the inhibition generated by the GTO typically occurs in an effort to avoid excess force against an external object or near end range, which we did not test.⁸ Our study was performed with subjects in an externally rotated position, whereas internal rotation movement releases tension within the anterior portion of the shoulder capsule, minimizing contributions from joint receptors.^{14,35}

Additional loads for the VF and PF conditions generated slower peak rotational velocities. The Fitts law dictates that movement accuracy decreases linearly with faster movement speeds, whereas slower movements tend to be more accurate.³⁶ Additional loads can dampen the initial peak velocity, which could make it easier to achieve target position. When move-

ment accuracy and consistency are being evaluated, slower movements do not necessarily result in better performance. The complex interaction among multiple proprioceptive inputs that can influence the ability to accurately move to a target is beyond the scope of this study and warrants further investigation.

We report both the VF and PF conditions as a way to compare the influence of additional loads during these movements. The CE observed for the unloaded condition was between the 2.7° reported by Safran et al³⁷ and the 6° reported by Lee et al.³⁸ The 3.1° of VE we report for the unloaded condition is less than the 4° reported for passive external rotation by Janwantanakul et al³⁹ and the 3.3° for internal rotation reported by Dover and Powers.⁴⁰ The 4.6° of AE we report for the unloaded condition is between the 4.5° reported by Dover et al⁴⁰ for internal rotation movements and the 6° reported by both Janwantanakul et al³⁹ and Rogol et al⁴ for external rotation movements. Although methodologic differences could account for these small differences in shoulder JPS outcomes, our data are consistent with those of previous studies.

We report differences in VE between the unloaded and loaded conditions, with no such difference in CE and AE. This is in agreement with the thought that CE and AE evaluate accuracy, whereas VE is more representative of the consistency of a performance.^{19,41} However, reporting CE also results in a directional bias to accuracy but not consistency, which is not encapsulated with AE.¹⁹ Overshooting a target tends to produce positive values for CE, demonstrated in this study during the PF movement condition, whereas undershooting produces negative values for CE. Clark et al⁴² contended that CE represents a systematic error, and this measure provides information about the “calibration” or “internal bias” of kinesthetic position sense. Clark et al⁴² also suggested that VE is better suited to represent overall performance of movements. Schmidt and Lee¹⁹ suggested that VE continues to improve with practice, whereas CE remains fairly constant for active movements. We believe that using 3 measures of a performance, such as CE, VE, and AE, increases the ability to identify subtle differences during shoulder JPS that could indicate differences in CNS feedback and subsequent movement control.

STUDY LIMITATIONS

Movements that include direct VF are referred to as the VF condition, and movements in the absence of vision are referred to as the PF condition. Although we acknowledge the presence of proprioceptive feedback during the VF condition, we categorized this condition according to the main feedback via vision.

It is unclear if a restricted single degree-of-freedom movement, such as glenohumeral internal rotation with the upper extremity contained within a shoulder wheel apparatus, has any application to movement accuracy during unrestricted upper extremity movements. If not, we could question all results from studies of single-joint measurements of joint kinesthesia in the upper extremity. Single-plane, restricted movements appear to bias measures of motor performance.^{19,42} However, it has not been demonstrated if performance measures from a movement restricted to a single degree of freedom have any significance on 3-dimensional functional movements. Additionally, we provided VF through a video monitor in 2-dimensional space, compared with the usual 3-dimensional VF

encountered during normal daily function. Restricting movements to a single plane and providing 2-dimensional feedback could limit the interpretations of this study. Moreover, we did not calculate effect sizes a priori, but a post hoc analysis demonstrated large effect sizes ($d > 1$) between the VF and PF conditions and small effect sizes between the unloaded and unloaded conditions for CE ($d = 0.03$), VE ($d = 0.38$), and AE ($d = 0.0$). These findings suggest that even though statistical significance was demonstrated in VE between the loaded and unloaded conditions, small effect sizes require cautious interpretation, with further study needed to corroborate the outcomes observed here.

It is unclear if PF during active target replication is influenced by the level of muscle activity. Athletes who perform overhead tasks have demonstrated delayed muscle activation patterns in response to sudden changes in position and diminished ability to detect passive position changes.^{25,28} Subjects were presented the target for the PF condition and then proceeded to actively move to the target. Passive movements are thought to stimulate mechanoreceptors using a different mechanism than active movements. Specifically, the contribution of the gamma motor system influences spindle sensitivity, thus affecting the active replication after passive presentation of a target.⁸ Palliard and Brouchon⁴³ suggested that active positioning is more accurate than passive positioning, possibly reducing any error associated with this paradigm. The passive presentation of the arm position was an attempt to establish a reference system for each subject. Whether this is an externally or internally based system is debatable. However, with multiplanar upper extremity reaching movements, no difference in accuracy has been demonstrated when the target is passively as opposed to actively presented.^{44,45} Although we provided frequent breaks to subjects, we made no attempt to control the duration or number of breaks. Subjects were instructed to move to the target position, with either VF of the target on the video screen during the VF condition or immediately after passive presentation of the target position. Because presentation of the target preceded every PF trial, we felt no need to restrict breaks, as long as subjects reported feeling fine with repeated trials.

CLINICAL RELEVANCE

Studies of JPS in the shoulder typically occur in the laboratory setting. However, clinical assessments can be implemented with the use of inclinometers and commercially available dynamometers.^{4,39,40} The direct clinical applications for 0.5° differences are questionable, but this research is designed to identify how performance can be altered with the addition of weight and contributes to the knowledge of human function. Further research is needed to explore the scientific reasons behind the changes identified in this study. Moreover, VE appears to be sensitive enough to identify differences in JPS at the shoulder. It has been reported that VE is more amenable to change and would be a good clinical indicator of improvement after rehabilitation or training.¹⁹ Continued clinical research is needed to determine if these factors can be measured in the clinic or remain in the domain of the laboratory setting; however, it is important, once we identify how loaded movements can influence JPS, to transfer these types of tests into the clinic for practical applications. Clinicians must not forget the influence of the GTO during proprioceptive testing.

CONCLUSIONS

Methods of assessing shoulder JPS when active movements are used should include the addition of an extra load to incorporate the contributions of the GTO. Multiple measures of performance, such as CE, VE, and AE, may be needed to fully assess patient function.²⁴ Although differences between loaded and unloaded movements might result in subtle differences in VE, future clinical testing is necessary to fully determine the influence of external loads on active movements during shoulder JPS tests. Additional research is required to determine the CNS mechanisms behind active movements that rely on kinesthetic feedback and how an external load influences this type of assessment.

ACKNOWLEDGMENTS

This study was partially funded by the Kentucky Physical Therapy Association, Verona, KY. The data presented here were part of a larger study that encompassed and examined other movement conditions. Parts of these data were originally presented at the 55th NATA Annual Meeting and Clinical Symposium, Baltimore, MD. We thank the NCI Fellows Editorial Board for editorial assistance.

REFERENCES

1. Lephart SM, Warner JJ, Borsa PA, Fu FH. Proprioception of the shoulder joint in healthy, unstable and surgically repaired shoulders. *J Shoulder Elbow Surg.* 1994;3:371–380.
2. Smith RL, Brunolli J. Shoulder kinesthesia after anterior glenohumeral joint dislocation. *Phys Ther.* 1989;69:106–112.
3. Gordon J, Ghez C. Muscle receptors and spinal reflexes: the stretch reflex. In: Kandel ER, Schwartz JH, eds. *Principles of Neural Science.* New York, NY: Elsevier Science; 1985:443–456.
4. Rogol IM, Ernst G, Perrin DH. Open and closed kinetic chain exercises improve shoulder joint reposition sense equally in healthy subjects. *J Athl Train.* 1998;33:315–318.
5. Rothwell JC, Traub MM, Day BL, Obeso JA, Thomas PK, Marsden CD. Manual motor performance in a deafferented man. *Brain.* 1982;105(pt 3): 515–542.
6. Ghez C, Gordon J, Ghilardi MF. Impairments of reaching movements in patients without proprioception, II: effects of visual information on accuracy. *J Neurophysiol.* 1995;73:361–372.
7. Gordon J, Ghilardi MF, Ghez C. Impairments of reaching movements in patients without proprioception, I: spatial errors. *J Neurophysiol.* 1995; 73:347–360.
8. Carew TJ, Ghez C. Muscles and muscle receptors. In: Kandel ER, Schwartz JH, eds. *Principles of Neural Science.* New York, NY: Elsevier; 1985:443–456.
9. Burgess PR, Wei JY, Clark FJ, Simon J. Signaling of kinesthetic information by peripheral sensory receptors. *Annu Rev Neurosci.* 1982;5:171–187.
10. Macefield G, Gandevia SC, Burke D. Perceptual responses to microstimulation of single afferents innervating joints, muscles and skin of the human hand. *J Physiol.* 1990;429:113–129.
11. Burke D, Gandevia SC, Macefield G. Responses to passive movement of receptors in joint, skin and muscle of the human hand. *J Physiol.* 1988; 402:347–361.
12. Millar J. Joint afferent fibres responding to muscle stretch, vibration and contraction. *Brain Res.* 1973;63:380–383.
13. Moberg E. The role of cutaneous afferents in position sense, kinesthesia, and motor function of the hand. *Brain.* 1983;106(pt 1):1–19.
14. Newton RA. Joint receptor contributions to reflexive and kinesthetic responses. *Phys Ther.* 1982;62:22–29.
15. Houk JC, Henneman E. Responses of Golgi tendon organs to active contractions of the soleus muscle of the cat. *J Neurophysiol.* 1967;30:466–481.
16. Crago PE, Houk JC, Rymer WZ. Sampling of total muscle force by tendon organs. *J Neurophysiol.* 1982;47:1069–1083.

17. Houk JC, Singer JJ, Henneman E. Adequate stimulus for tendon organs with observations on mechanics of ankle joint. *J Neurophysiol.* 1971;34:1051–1065.
18. Lundberg A. Control of spinal mechanisms from the brain. In: Tower DB, ed. *The Nervous System: The Basic Neurosciences*. Vol 1. New York, NY: Raven Press; 1975:253–265.
19. Schmidt RA, Lee TD. *Motor Control and Learning*. Champaign, IL: Human Kinetics; 1999.
20. Smoll FL, Schutz RW. Relationships among measures of preferred tempo and motor rhythm. *Percept Mot Skills.* 1978;46(3 pt 1):883–894.
21. Magee DJ. *Orthopedic Physical Assessment*. Philadelphia, PA: WB Saunders; 1987.
22. Karara HM, Abdel-Aziz YI. Accuracy aspects of non-metric imageries. *Photogram Eng.* 1974;40:1107–1117.
23. Winter DA. *Biomechanics and Motor Control of Human Movement*. New York, NY: John Wiley & Sons, Inc; 1990.
24. Brindle TJ, Nitz AJ, Uhl TL, Kifer E, Shapiro R. Measures of accuracy for active shoulder movements at 3 different speeds with kinesthetic and visual feedback. *J Orthop Sports Phys Ther.* 2004;34:468–478.
25. Brindle TJ, Nyland J, Shapiro R, Caborn DNM, Stine R. Shoulder proprioception: latent muscle reaction times. *Med Sci Sports Exerc.* 1999;31:1394–1398.
26. Edin BB, Johansson N. Skin strain patterns provide kinesthetic information to the human central nervous system. *J Physiol.* 1995;487(pt 1):243–251.
27. Essick GK, Bredehoeft KR, McLaughlin DF, Szaniszlo JA. Directional sensitivity along the upper limb in humans. *Somatosens Mot Res.* 1991;8:13–22.
28. Allegrucci MA, Whitney SL, Lephart SM, Irrgang JJ, Fu FH. Shoulder kinesthesia in healthy unilateral athletes participating in upper extremity sports. *J Orthop Sports Phys Ther.* 1995;21:220–226.
29. Wallace DA, Beard DJ, Gill RH, Eng B, Carr AJ. Reflex muscle contraction in anterior shoulder instability. *J Shoulder Elbow Surg.* 1997;6:150–155.
30. Hore J, Watts S, Tweed D. Errors in the control of joint rotations associated with inaccuracies in overarm throws. *J Neurophysiol.* 1996;75:1013–1025.
31. Johnston TB. The movements of the shoulder joint: a plea for the use of the “plane of the scapula” as the plane of reference for movements occurring at the humeroscapular joint. *Br J Surg.* 1937;25:252–260.
32. Rymer WZ, D’Almeida A. Joint position sense: the effects of muscle contraction. *Brain.* 1980;103:1–22.
33. Watson JD, Colebatch JG, McCloskey DI. Effects of externally imposed elastic loads on the ability to estimate position and force. *Behav Brain Res.* 1984;13:267–271.
34. Worringham CJ, Stelmach GE. The contribution of gravitational torques to limb position sense. *Exp Brain Res.* 1985;61:38–42.
35. Williams WJ. A systems-oriented evaluation of the role of joint receptors and other afferents in position and motion sense. *Crit Rev Biomed Eng.* 1981;7:23–77.
36. Fitts PM, Bahrick HP, Nobel ME, Briggs GE. *Skilled Performance*. Columbus, OH: Ohio State University; 1959:657–670.
37. Safran MR, Borsa PA, Lephart SM, Fu FH, Warner JJ. Shoulder proprioception in baseball pitchers. *J Shoulder Elbow Surg.* 2001;10:438–444.
38. Lee HM, Liao JJ, Cheng CK, Tan CM, Shih JT. Evaluation of shoulder proprioception following muscle fatigue. *Clin Biomech (Bristol, Avon).* 2003;18:843–847.
39. Janwantanakul P, Magarey ME, Jones MA, Dansie BR. Variation in shoulder position sense at mid and extreme range of motion. *Arch Phys Med Rehabil.* 2001;82:840–844.
40. Dover G, Powers ME. Cryotherapy does not impair shoulder joint position sense. *Arch Phys Med Rehabil.* 2004;85:1241–1246.
41. Romaguere P, Anton JL, Roth M, Casini L, Roll JP. Motor and parietal cortical areas both underlie kinaesthesia. *Brain Res Cogn Brain Res.* 2003;16:74–82.
42. Clark FJ, Larwood KJ, Davis ME, Deffenbacher DA. A metric for assessing acuity in positioning joints and limbs. *Exp Brain Res.* 1995;107:73–79.
43. Paillard J, Brouchon M. Active and passive movements in the calibration of position sense. In: Freedman SJ, ed. *The Neuropsychology of Spatially Oriented Behavior*. Homewood, IL: Dorsey Press; 1968:37–55.
44. Adamovich SV, Berkinblit MB, Fookson O, Poizner H. Pointing in 3D space to remembered targets. I: kinesthetic versus visual target presentation. *J Neurophysiol.* 1998;79:2833–2846.
45. Darling WG. Perception of forearm angles in 3-dimensional space. *Exp Brain Res.* 1991;87:445–456.