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RESEARCH ARTICLE

No Relationship Between Joint Position Sense and Force Sense at the Shoulder

David Phillips*, Andrew Karduna
Department of Human Physiology, University of Oregon, Eugene.

ABSTRACT. In practice, a single test is used to quantify an individual's proprioception. Previous studies have not found a correlation between joint position sense (JPS) and force sense (FS), which are submodalities of proprioception. The purpose of the present study is to determine if root mean square (RMS) error in JPS and FS are related at the shoulder, controlling for external load and elevation angle. Active shoulder angle and force reproduction protocols were performed. No correlation was found between JPS and FS ($r = -.019$, $p = .941$) nor were any individual angle and load combinations significant. The main effect for angle in JPS was significant ($p < .001$). Follow-up contrast demonstrated a significant ($p < .001$) decrease in RMS error with increased elevation. A significant load by angle interaction was found for FS ($p = .014$). Follow-up simple effects tests by angle demonstrated RMS error decreased with load at 50° and 70° but not at 90°. By load, RMS error only decreased for 120% between 50° and 90°. JPS and FS demonstrate different behavior with load and angle. This differing behavior is more likely responsible for the lack of correlation than angle and load differences in JPS and FS protocols.

Keywords: correlation, force sense, joint position sense, proprioception, shoulder

Proprioception is the ability to determine the movement status and position of a limb in space without the use of vision. Poor proprioception at a joint may result in the increased likelihood of injury (Blasier, Carpenter, & Huston, 1994) and proprioceptive deficits in an injured population have been documented by comparing a dysfunctional or injured joint to either the unaffected side or to a healthy population (Anderson & Wee, 2011; Kim, Choi, & Kim, 2014; Maenhout, Palmans, De Muynck, De Wilde, & Cools, 2012; Relph, Herrington, & Tyson, 2014). However, different tests are administered to test proprioception depending on whether the researcher is assessing joint position sense (JPS), force sense (FS), or kinesthesia. While JPS can be evaluated using passive or active protocols, FS is always assessed with an active muscle contraction (Han, Waddington, Adams, Anson, & Liu, 2015; Proske & Gandevia, 2012). FS can be evaluated with ipsilateral and contralateral remembered protocols or concurrent contralateral protocols.

There is likely a relationship between these submodalities, as similar pathways and sensory receptors are active during when each is assessed. This is particularly true during active protocols, where muscle tension must be developed in both protocols. The processes active in FS may therefore also be playing some role in JPS (J. A. Winter, Allen, & Proske, 2005). The processes would include gathering and integrating sensory information from receptors located in the periphery (muscle spindles, Golgi Tendon organs, cutaneous receptors, and joint receptors) and the centrally generated sense of effort (Proske & Gandevia, 2012).

With one exception for ankle eversion, studies investigating the relationship between JPS and FS have not found a significant or high correlation between the two submodalities. (Docherty, Arnold, Zinder, Granata, & Gansneder, 2004; Kim et al., 2014; Li, Ji, Li, & Liu, 2016). Deficits in proprioception may place an individual at greater risk of injury (Blasier et al., 1994). If different aspects of proprioception are unrelated, then a single test may not identify all proprioceptive deficits. Undetected deficits cannot be treated, leaving the individual at risk of injury. Complicating the assessment of proprioception is that the submodalities may be affected differently if there is an injury. For example, at the ankle, FS deficits are evident but JPS is unaffected by functional ankle instability (Docherty, Arnold, Gansneder, Hurwitz, & Gieck, 2004).

It is possible that previous studies have not detected a correlation between JPS and FS due to significant methodological differences, in terms of joint angle and load. Previous work from our lab has demonstrated that both load and angle have significant effects on JPS at the shoulder and elbow, with decreased errors at higher angles of shoulder elevation (King, Harding, & Karduna, 2013; Suprak, Osternig, van Donkelaar, & Karduna, 2006). To our knowledge, the effect of different joint angles and loads have yet to be investigated in a FS protocol. Of the studies investigating a correlation between JPS and FS, only Li et al. (2016) conducted a FS protocol at the same joint targets used in the JPS protocol. That study also found no relationship between JPS and FS.

Force targets are typically set at percentages of a maximum voluntary contraction, while JPS targets are set at specific angles (Docherty et al., 2004; Kim et al., 2014; Li et al., 2016). When targets are set in this way, the amount of torque generated during FS protocols will be higher than in JPS protocols at the target position. This is because in FS the muscles must first overcome the weight of the limb before a force can be applied while in JPS only the limb's

Correspondence address: Andrew Karduna, Department of Human Physiology, 122 Esslinger Hall, 1240 University of Oregon, Eugene, OR, 97403-1299. E-mail: karduna@uoregon.edu
**Present address: Department of Exercise Science and Physical Education, Montclair State University.*
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weight needs to be supported. Additionally, force control in the upper extremity has been shown to be less variable than in the lower extremity (Christou, Zelent, & Carlton, 2003). This lower degree of variability may make the joints of the upper extremity more appropriate to examine the relationship between JPS and FS.

The purpose of this study was to determine if JPS and FS are related at the shoulder when external load and joint angle are the same between the protocols. The second purpose of this study was to determine the effect of angle and load on FS. We hypothesized that there would be a positive correlation between JPS and FS. We further hypothesized that the behavior of JPS and FS would be the same and error would decrease at higher angles and loads for both.

Material and Methods

Subjects

Eighteen healthy subjects (nine men, nine women, M age $= 25.8 \pm 3.6$ years, M weight $= 70.7 \pm 11.8$ kg, M height $= 171.1 \pm 8.6$ cm, 16 right handed and two left handed) were tested. One additional subject was tested, however due to equipment error, the subject did not complete the experiment. Subjects self-reported hand dominance by indicating the hand they used to write. Subjects were included in the study if they were between 18 and 40 years old. Exclusion criteria included previous shoulder or neck injuries that required medical attention, current shoulder or neck pain, humeral elevation range of motion less than 135°, and pregnancy. The subjects were briefed on the purpose and the experimental procedure prior to the start of the experiment and completed an informed consent form. The experiment received ethical clearance from the Internal Review Board at the University of Oregon and all subjects provided written consent.

Instrumentation

The force acting on the forearm immediately proximal of the ulna styloid process was recorded using a uniaxial load cell (Lebow Products, Troy, MI, Model 3397-50) during FS. Force data were sampled at 100 Hz with custom LabVIEW software (LabVIEW v12.0, National Instruments, Austin, TX). The forearm was flush with the surface of the load cell, in the thumbs-up position with the elbow fully extended and secured with custom nonelastic lifting Velcro straps. The load cell was adjusted for each humeral elevation angle being tested (50°, 70°, and 90°). A head mounted display (Z800, eMagine, Bellevue, WA) provided visual guidance to targets during the JPS and FS protocols and was modified to block all vision of the shoulder and arm and external light sources.

Thoracic, scapular and humeral kinematics were sampled at 120 Hz with a magnetic tracking device (Polhemus Liberty, Colchester, VT), which included a transmitter, three sensors, and a digitizer. The sensors were mounted on the manubrium of the sternum, the flat area of the acromion, as well as on the distal humerus via a custom-molded Orthoplast cuff and Velcro strap (Ludewig and Cook, 2000; Suprak et al., 2006). The transmitter was positioned posterior and contralateral to the testing arm of the subject. The subject sat on an ergonomically designed kneeling chair (Better Posture Kneeling Chairs, Jobri, Konawa, OK) for both protocols.

Anatomic landmarks were palpated and digitized, using the standards recommended by the International Society of Biomechanics (ISB; Wu et al., 2005), with the first option used to set the humeral coordinate system. Based on the ISB standard, for humerothoracic motion, the following Euler sequence was used: plane of elevation, elevation, and axial rotation (Wu et al., 2005).

Protocol

Testing was completed in a single session. After weight, height, arm length (acromion process to radial styloid process), and hand length (midpoint between styloid processes to knuckle II) were measured with a tape measure, subjects sat on an ergonomic kneeling stool with no back support, with minimized tactile cues from the back during testing. The calculation of force targets in the FS and weights in JPS was based on anthropometric measurements (D. Winter, 2005), so that the target torque experienced at the shoulder was equal between the two protocols. Target torque was a function of baseline torque, which was considered to be the torque with no extra weights. The order of protocol (JPS and FS) was randomized.

We used an active angle reproduction JPS protocol previously developed in our lab, with minor modifications (King et al., 2013). This protocol uses horizontal white lines on the head mounted display to guide the subject to a target joint angle. The instructions, timing and visual feedback were therefore consistent between the JPS and FS protocols. In both JPS and FS, the subject would memorize a target humeral elevation angle or force for 3 s. The subject would then return the arm to the side for JPS and relax the shoulder muscles for FS. The time to relax was 2 s. The final phase would require the subject to reproduce the humeral elevation angle or force without visual feedback. The subject would push a trigger held in their free hand when he or she believed the target had been reproduced. The first modification for this study was that the white lines on the display during the target memorization period did not disappear until the subject was instructed to relax. The second was that the line guiding the subject to a target would represent the glenohumeral elevation angle during JPS and force applied to the load cell during FS. Prior to the first instance of the JPS or FS protocol, six practice trials were given.

For the JPS protocol, there were three target humeral elevation positions (50°, 70°, and 90°) in the scapular plane

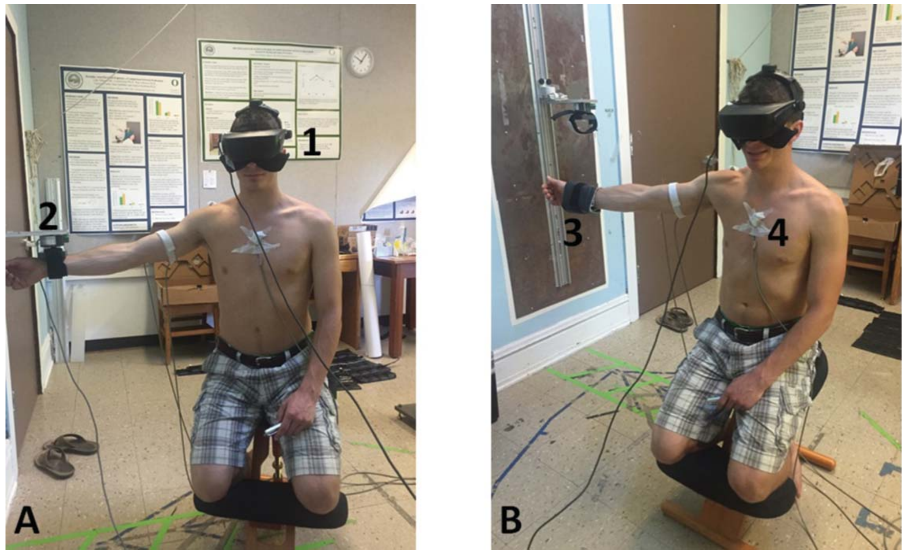

FIGURE 1. Experimental setup for FS (A) and JPS (B). 1) Head-mounted display 2) Bracket and load cell set flush with the forearm at 90° humeral elevation 3) Wrist weight 4) Thoracic magnetic sensor. Additional sensors were placed on the distal humerus and acromion process. All testing was performed in the scapula plane.

(35 ± 4° anterior of the coronal plane). Each target position was repeated four times, resulting in 12 trials. The JPS protocol was repeated for each external load (120%, 140%, and 160% of baseline torque) with a break of 5 min between each block of 12 trials. In each repetition of the JPS protocol a weight was placed on the wrist that would increase the torque at each angle to 120%, 140%, and 160% of baseline torque (Figure 1B). The order of testing for targets and weights was randomized. Loads were based on the previous research (Suprak, Osternig, van Donkelaar, & Karduna, 2007) and pilot testing indicated that subjects were comfortable completing trials at each target load.

For the FS protocol there were three force targets, with the arm secured to the load cell with a modified nonelastic lifting strap at the humeral elevation angle of interest (50°, 70°, and 90 ± 1° elevation) in the scapular plane (Figure 1A). This was done with real-time kinematic feedback from the magnetic tracking system so that testing angles in the FS protocol would be the same as the target angles in the JPS protocol. Each target force was repeated four times, resulting in 12 trials. The FS protocol was repeated for each humeral elevation angle (50°, 70°, and 90°) with a break of 5 min between each block of 12 trials. The force targets were calculated to be the applied force to the load cell would be 120%, 140%, and 160% of baseline torque. As with the JPS protocol, the order of testing for targets was randomized.

Data Analysis

Angles from the JPS protocol were converted into torque values (Nm) as follows. The wrist weight torque was calculated using the humeral elevation angle, arm length, and mass (kg) of the wrist weight. Torque due to the weight of the arm was added to the torque due to the wrist weight to get the total torque value for the presented and reproduced, when the subject pressed the trigger, angles. In the FS protocol the force level during memorization and the reproduced force level, when the subject pressed the trigger, were measured in Newtons. These forces were then converted into torque values (Nm) using the force measured from the load cell acting perpendicularly to the forearm and the length of the arm. The torque measured from the load cell was added to baseline torque for the current humeral elevation angle. The average of the torque during the memorization period was termed presented torque and the instantaneous torque when the subject pressed the trigger button was termed reproduced torque.

Root mean square (RMS) error was calculated for each angle and load level (e.g., 70° at 120% of baseline torque) in both protocols and normalized to presented torque level (120%, 140%, and 160% of baseline torque).

$$\text{RMS error} = \sqrt{\sum \left(\frac{(x_i - T)}{T} * 100 \right)^2 / n}$$

Where x_i is reproduced torque, T is presented torque, and n is the number of trials. The average of the four trials at each load and angle combination was calculated. In almost all cases, there were four viable trials. However in some instances subjects did not perform the protocol correctly (e.g., relaxing during memorization) or the trigger did not register, resulting in three viable trials in 17

(11%) cases for FS and five (3%) cases for JPS. In these cases the average of three trials was calculated.

Statistical Analysis

Statistical analysis was performed using SPSS version 22.0. A Pearson correlation coefficient was calculated to determine the relationship between the subjects' averaged score across all JPS conditions and the averaged score across all FS conditions in RMS error normalized to target. The correlation between averaged JPS and overall FS normalized RMS error was determined by Pearson correlation analysis with a linear regression model with normalized RMS error data averaged for each subject across all loads and angles. The averaged subject score was calculated by averaging each subject's normalized RMS error score for each condition to indicated ability across all angles and loads for each protocol. Additional Pearson correlations were calculated for each angle and load condition between JPS and FS normalized RMS error. For example, the correlation coefficient was calculated for JPS and FS at 50° humeral elevation at 120% of baseline torque.

A three-way repeated measures analysis of variance (ANOVA) was used to assess the effect of protocol (JPS and FS), elevation angle (50°, 70°, and 90°) and load (120%, 140%, and 160% of baseline torque) on normalized RMS error. A significant three-way interaction will have two follow-up two-way ANOVAs run for JPS and FS to assess the effect of elevation angle (50°, 70°, and 90°) and load (120%, 140%, and 160% of baseline torque) on normalized RMS error. In the case of a significant two-way interaction, follow-up comparisons of simple effects using a Bonferroni adjust were run. Follow-up comparisons were run for significant main effects using a Bonferroni adjustment. An a priori alpha level of .05 was set for all tests.

Results

Correlations between JPS and FS

No significant correlation for overall normalized RMS error between FS and JPS was found, $r = -.019$, $p = .941$ (Figure 2). Neither was there a significant correlation for normalized RMS error between FS and JPS at any angle or load combination (Table 1).

A significant three-way interaction for protocol by angle by load was found on normalized RMS error, $F(4, 68) = 22.9$, $p = .024$. In the follow-up two-way ANOVA for normalized RMS error in the JPS protocol, Mauchly's test indicated the assumption for sphericity had been violated for angle by load interaction, $\chi^2(9, N =) = 53.69$, $p < .001$, and for the angle main effect, $\chi^2(2, N =) = 35.78$, $p < .001$. The degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity, $\varepsilon = 0.41$ for the angle by load interaction and $\varepsilon = 0.53$ for the angle main effect. The results showed for normalized RMS error in the JPS protocol did not demonstrate a significant interaction effect $F(1.6, 27.6) = 0.50$, $p = .58$, or a main effect for load, $F(2, 34) = 0.8$, $p = .47$, but the main effect for angle was significant, $F(1.1, 18.0) = 209.00$, $p < .001$,. A follow-up contrast demonstrated a significant ($p < .001$) linear decrease in error with increasing humeral elevation (Table 2).

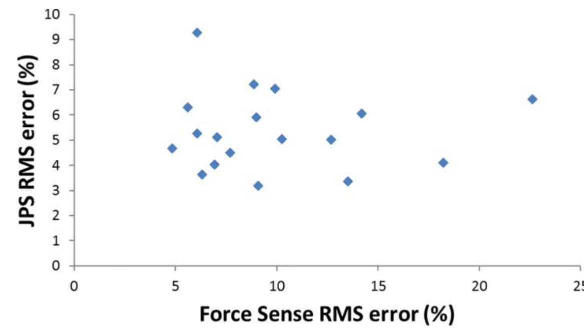

FIGURE 2. Average JPS and FS RMS error across all angles and load conditions and normalized to presented torque level.

The follow-up two-way ANOVA for normalized RMS error in the FS protocol found a significant interaction between load and angle, $F(4, 68) = 40.00$, $p = .014$. Follow-up simple effects tests for angle by load showed significant decreases in normalized RMS error at 50° from 120% to 140% ($p = .001$), from 120% to 160% ($p < .001$), and from 140% to 160% ($p < .01$); at 70° from 120% to 160% ($p = .001$) and from 140% to 160% ($p = .019$). No significant decrease in normalized RMS error was found for any load at 90°. Follow-up simple effects tests for load by angle only showed a significant decrease in normalized RMS error at 120% from 50° to 90° ($p = .034$; Table 3).

TABLE 1. Pearson Correlation Coefficients between JPS and Force Sense for Each Shoulder Elevation Angle and Load

Angle	Load	Correlation coefficient
50°	120%	−0.12
50°	140%	0.30
50°	160%	−0.01
70°	120%	−0.03
70°	140%	−0.15
70°	160%	0.11
90°	120%	0.19
90°	140%	−0.42
90°	160%	0.35

Note: No correlations were significant

TABLE 2. RMS Error Normalized to Target Means and Standard Error of the Mean Between Angles and Loads for Joint Position Sense

	50° Elevation (SEM)	70° Elevation (SEM)	90° Elevation (SEM)	Total
120% Baseline	12.1 (1.1)	3.4 (0.3)	0.6 (0.1)	5.4 (0.5)
140% Baseline	11.7 (0.7)	3.4 (0.3)	0.5 (0.1)	5.2 (0.4)
160% Baseline	12.4 (0.9)	3.5 (0.3)	0.6 (0.1)	5.5 (0.4)
Total	12.1 (1.1)*	3.4 (0.3)*	0.6 (0.1)*	5.4

Note: * indicates significant difference between angles ($p < 0.05$).

Discussion

The primary purpose of the study was to determine if JPS and FS at the shoulder are related when load and angle are controlled between the two protocols. The secondary purpose was to determine the effect of load and angle on FS. We found no significant relationship between FS and JPS overall, or at each angle and load combination (Table 1). Our correlation coefficient of –.019 is consistent with the previous studies at the knee and ankle where nonsignificant correlations of .01–.35 have been found (Docherty et al., 2004; Kim et al., 2014; Li et al., 2016). The exception being the correlation coefficient of .65 between JPS and FS during eversion at the ankle in the study by Docherty et al. Contrary to our hypothesis, accounting for load and angle between JPS and FS indicated that JPS performance predicts < 0.001% of the variance in FS. The individual correlation values for each angle and load varied across the conditions, but all were not significant and within the range previously reported by the other studies.

The low correlation values may be due to the differing behavior between FS and JPS. We hypothesized that both FS and JPS, error would decrease at higher loads and angles of elevation. However, only a main effect of angle was found in JPS and an angle by load interaction effect was found in FS. The effect of decreasing error in JPS with increased elevation found in this study is consistent with previous research in our laboratory (Suprak et al., 2006). However the effect of load previously observed (Suprak et al., 2007) was not seen. Decreased error in that study was seen between 110% of baseline torque and 130% and 140% at 50° humeral elevation. This study utilized 120%, 140%, and 160% and no effect of load was seen for JPS at any humeral elevation angle. It would seem that a slight advantage is gained at very light additional loads (110%) but loads between 120% to 160% of baseline torque do not provide any improvement or decrement.

Conversely, for FS, an interaction effect for load by angle was found. For the load analysis, no follow-up tests were significant for 90° humeral elevation. At 70° humeral elevation normalized RMS error decreased from 120% to 160% and from 140% to 160%. At 50° humeral elevation normalized RMS error decreased from 120% to 140%, 120% to 160%, and 140% to 160%. In the angle analysis, the only follow-up test that was significant showed a decrease in normalized RMS error between 50° to 90° for the 120% load.

A number of factors may be at play causing this interactive result between angle and load. Mechanically, the moment arms of the deltoid and supraspinatus lengthen and shorten respectively with higher elevations (Ackland, Pak, Richardson, & Pandy, 2008). The activation characteristics and length-tension relationship of muscles also changes with joint angles (Rassier, MacIntosh, & Herzog, 1999; Saito & Akima, 2013). The greatest torque is encountered when the arm is at 90° humeral elevation. This means that the targets set as a function of baseline torque would be greatest at this angle. These mechanical changes make it difficult to determine if the afferent feedback and sense of effort at the 50° and 70° humeral elevation loads are

TABLE 3. RMS Error Normalized to Target Means and Standard Error of the Mean Between Angles and Loads for Force Sense

	50° Elevation (SEM)	70° Elevation (SEM)	90° Elevation (SEM)	Total
120% Baseline	14.9 (2.0)*[a]	12.4 (1.7)[b]	10.6 (1.5)*	12.6 (1.7)
140% Baseline	10.9 (1.4)[a]	9.6 (1.5)[c]	8.7 (1.3)	9.7 (1.4)
160% Baseline	7.2 (1.1)[a]	6.6 (0.9)[b c]	8.7 (1.3)	7.5 (1.1)
Total	11.0 (1.5)	9.5 (1.4)	9.3 (1.4)	9.9

Note: [a, b, c] indicates significant load difference with Bonferonni adjustment ($p < 0.05$).
* indicates significant angle difference with Bonferonni adjustment ($p < 0.05$).

equivalent to that at 90° humeral elevation. The feedback at lower angles may be more distinctive between loads.

Sense of effort also makes contributions to JPS accuracy. In a contralateral JPS protocol, decreased accuracy is seen when the reference arm is supported and muscle are relaxed. If additional weight is placed on the reference arm, errors are made in the direction of the movement caused by the contracting muscles (J. A. Winter et al., 2005). In our study, force targets in FS and weights for JPS were calculate so that the conditions would have the same torque output. It is unlikely that sense of effort is responsible for the differing behavior and lack of correlation between the two protocols.

The lack of relationship in normalized RMS error between the two protocols may also be due to variations in feedback from the peripheral mechanoreceptors during isometric and concentric contractions. When contracting a muscle both alpha and gamma (fusimotor) motor neurons fire simultaneously, which is referred to as alpha-gamma coactivation (Vallbo, 1970). This prevents a muscle spindle from becoming slack and unable to respond to the muscle lengthening. During isometric contractions, the agonist muscle's muscle spindles firing increases at an inconsistent rate (Vallbo, 1974). In this case the alpha-gamma coactivation may be attempting to shorten intrafusal muscle fibers that are remaining at the same length and applying tension on the muscle spindle increasing its firing rate. This would be the only signal from muscle spindles since during an isometric contraction the antagonist muscle will also remain at a constant length. However, it is argued that these fusimotor induced signals from muscle spindles during an isometric contraction are filtered out because they do not induce an illusion of movement at the joint (McCloskey, Gandevia, Potter, & Colebatch, 1983).

The incoming afferent information may therefore be very different between the two protocols. The brain may implement different strategies to interpret the afferent information during a FS compared to a JPS task. Given the lack of a correlation in the present study and others, it is possible that JPS and FS are independent of each other. A single proprioceptive test, JPS or FS, would be insufficient to quantify an individual's proprioception because they are independent.

It may be more important to determine which test best correlates with performance based outcomes or injury risk. Results from studies investigating knee JPS with functional based outcomes have shown that JPS can be unaffected but have different functional outcomes between healthy and affected sides (Kafa, Ataoglu, Hazar, Citaker, & Ozer, 2014; Naseri & Pourkazemi, 2012; Yosmaoglu, Guney, & Yuksel, 2013). However, free-throw percentage in basketball is higher in athletes with better upper extremity JPS (Kaya, Callaghan, Donmez, & Doral, 2012; Sevrez & Bourdin, 2015). FS- and performance-based outcomes warrant further investigation.

Limitations

Anthropometric measurements were made according to the protocol by Winter (1995). These were used to calculate the baseline torque, force targets during FS and weights for JPS. This is a limitation in the study because the force vector applied on the load cell may not result in the exact same torque as the gravity directed force vector from the wrist weight. Further, the cutaneous feedback at the wrist between the two protocols might also have differed. During the FS protocol the force vector will always be perpendicular to the wrist. During JPS the compression on the skin from the wrist weight will always act in the direction of gravity. This means the amount of perpendicular compression on the skin changes with humeral elevation during JPS. Last, laboratory testing of proprioception may not represent proprioceptive ability during daily movements.

Conclusions

The lack of a relationship between JPS and FS at the shoulder is not due to differing angles and loads between the different modality testing protocols. The relationship at the shoulder is also no different from what has been found in joints of the lower extremity. This may be due to FS and JPS being affected differently by load and angle. Last, assessment of only a single submodality of proprioception may not be sufficient to quantify an individual's proprioception.

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