***Motor Control,* (Ahead of Print)**
https://doi.org/10.1123/mc.2017-0067

Human Kinetics
ARTICLE

An Investigation Into Force Sense at the Shoulder

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Proprioception is assessed more often through joint position sense and kinesthesia than force sense. The purpose of this study is to investigate force sense at the shoulder. A total of 12 subjects were recruited. An ipsilateral force reproduction protocol at the shoulder at 50°, 70°, and 90° and 120%, 140%, and 160% baseline torque. Dependent variables were constant error (CE) and root mean square error. An effect was found for load on absolute ($p = .001$) and normalized CE ($p < .001$). CE decreased with increased load. An effect for angle was found for absolute root mean square error ($p = .002$), more accurate at 50° ($p = .01$), but no effect when normalized ($p = .19$). With increased loads, subjects undershot the target and CE approached zero. Because of the differing behavior in CE and root mean square error, and absolute and normalized data, force sense studies should examine error from these perspectives.

Keywords: force reproduction, isometric, proprioception

Proprioception is the integration of afferent information, from mechanoreceptors in the periphery, within the central nervous system for the conscious perception of limbs to maintain postural status and overall position in space (Han, Waddington, Adams, Anson, & Liu, 2015; Riemann & Lephart, 2002). Accurate information regarding position of limbs is necessary to successfully perform movements of daily living and athletic performance (Riemann & Lephart, 2002). Conscious interpretation of afferent proprioceptive information can be divided into three subdivisions: kinesthesia, joint position sense (JPS), and force sense.

JPS and kinesthesia are the most commonly assessed subdivisions of proprioception. The focus on JPS and kinesthesia is emphasized by the absence of force sense-related protocols in a recent critical review of proprioceptive

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methods (Han et al., 2015). This may be because muscle spindles are thought as the dominant mechanoreceptor for proprioception, detecting change in length and rate of change in length of a muscle occurring during JPS and kinesthesia testing (Proske & Gandevia, 2012). During force sense tasks, isometric contractions are used that may limit the contribution of muscle spindles since no muscle lengthening occurs. When a muscle contracts isometrically, the firing rate of muscles spindles does increase due to alpha-gamma motor neuron coactivation, but it is hypothesized that these impulses are filtered out as no movement illusions occur (McCloskey, Gandevia, Potter, & Colebatch, 1983). Another possible reason for lower focus on force sense is that no relationship has been identified between force sense and JPS or kinesthesia at any joint (Docherty, Arnold, Zinder, Granata, & Gansneder, 2004; Kim, Choi, & Kim, 2014; Li, Ji, Li, & Liu, 2016). As JPS and kinesthesia focus on joint angles, which arguably emphasize the mechanical receptor that is considered most important (muscle spindles), this lack of interrelationship between the subdivisions makes it difficult to establish the importance of force sense in clinical or athletic settings.

Proprioceptive assessment is performed on a range of joints depending on the study's focus. Han et al. (2015) reviewed proprioceptive measurement procedures at the ankle, knee, and shoulder. JPS research has an identified angle effect at the shoulder (Suprak, Osternig, van Donkelaar, & Karduna, 2006). Accuracy improves from lower humeral elevations up to 90°. This effect is robust across multiple follow-up studies (King, Harding, & Karduna, 2013; Edwards, Lin, King, & Karduna, 2016; Zanca, Mattiello, & Karduna, 2015). Kinesthesia has also been studied at the shoulder with better accuracy at 75° external rotation than neutral (Allegrucci, Whitney, Lephard, Irrgang, & Fu, 1995).

Most force sense studies do not utilize multiple load targets or different joint angles. Some studies have examined this effect at the ankle, knee, index finger, and shoulder using an ipsilateral force reproduction protocol. In two studies at the ankle, accuracy in force sense decreased with increasing load (Docherty & Arnold, 2008; Wright & Arnold, 2012), but another two studies showed no difference (Dos Santos Haupenthal et al., 2015; Smith, Docherty, Simon, Klossner, & Schrader, 2012). This same effect is not reflected at the knee (Iwańska, Karczewska, Madej, & Urbanik, 2015) or the index finger (Walsh, Taylor, & Gandevia, 2011). Another study at the knee (Li et al., 2016) and shoulder (Dover & Powers, 2003) did examine force sense at different joint angles but did not report angle effects. One ankle study did show a greater overshoot as load increased (Dos Santos Haupenthal et al., 2015), but the index finger showed the opposite trend (Walsh et al., 2011). No study has yet examined the effect of either load or angle at the shoulder in force sense. As poor proprioception may result in the development of injuries (Blasier, Carpenter, & Huston, 1994), characterizing all aspects of shoulder proprioception may lead to better treatment, prevention, and assessment techniques.

The purpose of this study is to investigate force sense at the shoulder at different shoulder elevation angles and target loads. We hypothesized that there would be a decrease in force sense error as elevation angle and external load increases, as was previously seen in JPS studies at the shoulder.

Methods

Subjects

A total of 12 healthy subjects were tested (6 males and 6 females; age: 21.3 ± 0.9 years; weight: 75.6 ± 12.3 kg). Subjects self-reported as being right-hand dominant, as indicated by the hand they used to write. Inclusion criteria included having a healthy shoulder and being between 18 and 40 years. Exclusion criteria included less than 135° of active humeral elevation in the scapular plane, prior shoulder and/or cervical surgery, presence or history of shoulder pain or pathology, and pregnancy. Subjects were briefed on the purpose of the study and the experimental procedure, and signed an informed consent form. The internal review board at the University of Oregon approved this study.

Experimental Setup

The force acting on a wrist cuff was recorded using a uniaxial load cell (model 3397-50; Lebow Products, Troy, MI). Force data were sampled at 100 Hz with custom LabVIEW software (LabVIEW v13.0; National Instruments, Austin, TX). Each subject's height, weight, arm length (acromion process to radial styloid process), and hand length (midpoint between styloid processes to the third knuckle) were measured with a tape measure to calculate baseline torque and force targets. These were calculated using anthropometric equations for torque due to the arm and the hand, which were summed to calculate baseline torque of the upper extremity (Winter, 2005).

Participants were attached to an external load cell by the wrist of their dominant arm using a nonelastic Velcro strap to keep their wrist secured to the apparatus. Their forearm was flush to the surface of the load cell and in a "thumbs-up" position with the elbow in full extension. They were also outfitted with a head-mounted display (Z800; eMagine, Bellevue, WA) to provide visual guidance and to eliminate visual cues from the environment (Figure 1).

Protocol

Each subject's data were collected in a single session. After their body measurements were measured and entered into the computer, the subject was then outfitted in the experimental setup. A target of two white horizontal lines were displayed on the head-mounted display. The subjects had to apply an upward force until their cursor (a red horizontal line) was in between the white target lines and maintained this force level for 3 s to memorize it. They were then given an automated verbal cue to relax. After 2 s, subjects were instructed to replicate the previous force without any visual feedback from the head-mounted display, and then, subjects notified the researcher when they felt they matched the previous force level. Once notified, the experimenter would hit a trigger, and the computer would record the force exerted. The subject was instructed to relax again. Subjects were allowed six practice trials to accustom them to the protocol. Once the practice trials were complete, data collection began.

Figure 1 — Experimental setup. Subjects were attached with a Velcro strap at the dominant wrist to a load cell (1) with a head-mounted display (2) providing visual feedback when guiding subjects to a force target. The load cell was mounted to a bracket that could change angles and height on the wall.

One memorization and reproduction of a torque level at a given angle was considered one trial. There were four trials of each target torque at each angle, making it a total of 12 trials for each angle. Torque targets were randomized and collected continuously at a given angle. Elevation angles were also randomized to prevent participant training and any order effect. Data were collected at three different angles of shoulder elevation (50°,70°, and 90°of shoulder elevation in the scapular plane) and at three target loads (120%, 140%, and 160% of baseline torque).

Data Analysis

Constant error (CE) and root mean square (RMS) error were calculated for analysis. CE is the difference between the reproduced torque and the presented torque target. This variable indicates the directionality, undershoot or overshoot of the target. RMS error indicates both the accuracy and consistency in reproducing the target load.

$$\text{Constant error} = \frac{\Sigma(x_i - T)}{n}$$

$$\text{RMS error} = \sqrt{\frac{\Sigma(x_i - T)^2}{n}},$$

where x is the torque reproduced in trial i, T is the target load in newton meters (N · m), and n is the number of trials. T is the sum of the torque due to the weight of the arm and the torque calculated with the force measured at the load cell. CE and RMS error are also calculated with the error normalized to the target load. Four trials were collected for each target load (120%, 140%, and 160% of baseline torque) at each humeral elevation angle (50°, 70°, and 90°).

Statistical Analysis

Statistics were run with SPSS version 22.0 (IBM Corp, Armonk, NY). Four 3 × 3 repeated-measure analysis of variance was used to assess the effect of target load (120%, 140%, and 160% of baseline torque) and angle (50°, 70°, and 90°) on absolute RMS error, absolute CE, normalized RMS error, and normalized CE. Follow-up comparisons were performed when appropriate using a Bonferroni adjustment for multiple comparisons.

Results

Absolute RMS Error

There was no significant interaction seen between angle and torque level, $F(4, 44) = 0.64$, $p = .63$. There was also no main effect found for target load, $F(2, 22) = 0.39$, $p = .68$. A significant main effect was found for angle, $F(2, 22) = 8.11$, $p = .002$. Follow-up t tests were performed with a Bonferroni adjustment for multiple comparisons. A significant difference was found between 50° ($M = 1.3$ N·m, $SD = 0.19$) and 90° ($M = 2.1$ N·m, $SD = 0.34$), $p = .01$ (Figure 2).

Absolute CE

The interaction between angle and torque target was not significant, $F(4, 44) = 0.72$, $p = .58$, and no main effect was found for angle, $F(2, 22) = 1.4$, $p > .27$. There was a significant main effect found for target load, $F(1.2, 12.6) = 18.9$, $p = .001$. A Greenhouse–Geisser adjustment made for the violation was sphericity, and

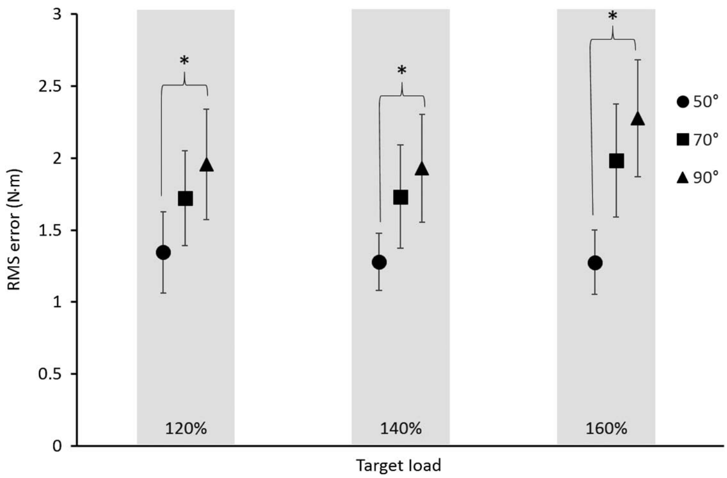

Figure 2 — Absolute RMS error for each angle and target load. The main effect for angle was significant, $p = .002$. Follow-up t-test comparisons found a significant difference only between 50° and 90°, $p = .01$. RMS = root mean square. *Significant difference between these angles at each load.

follow-up t tests were performed with a Bonferroni adjustment for multiple comparisons. Absolute CE was greater at 120% ($M = 1.3$ N·m, $SD = 0.37$) compared with 140% ($M = 0.77$ N·m, $SD = 0.43$) and 160% ($M = 0.2$ N·m, $SD = 0.5$), $p < .01$, and absolute CE was greater at 140% than 160%, $p < .01$ (Figure 3).

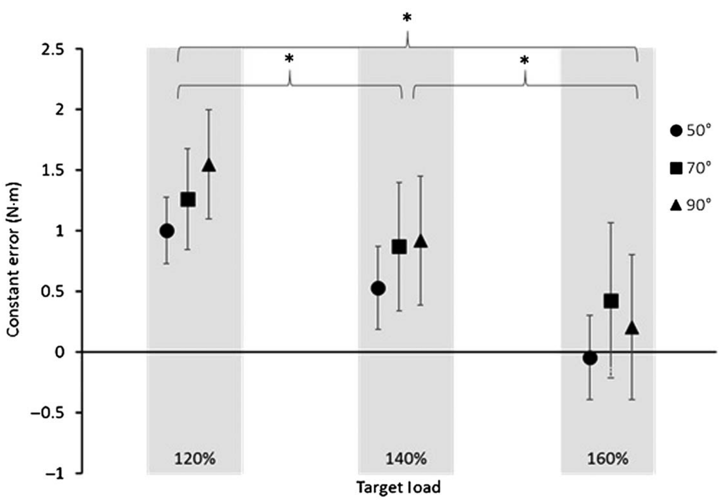

Figure 3 — Absolute constant error for each angle and target load. The main effect for load was significant, $p = .001$. Follow-up t tests found that the difference between each load condition was statistically significant, $p < .01$. *Statistically significant difference between loads.

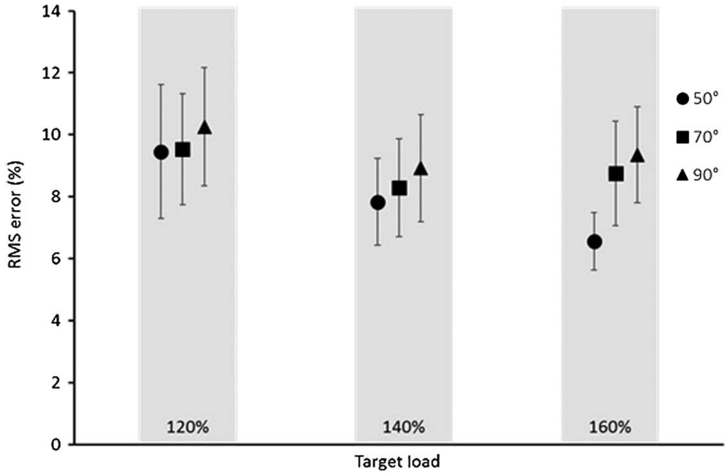

Figure 4 — Normalized RMS error for each load and angle. Neither the interaction effect nor the main effects were significant, $p > .05$. RMS = root mean square.

Normalized RMS Error

The interaction between angle and target load was not significant, $F(4, 44) = 0.82$, $p = .48$. No main effect was found for angle, $F(2, 22) = 2.2$, $p = .19$, and target load $F(2, 22) = 0.92$, $p = .56$ (Figure 4).

Normalized CE

There was no significant interaction between angle and target load, $F(4, 44) = 0.66$, $p > .66$. There was also no main effect was found for angle, $F(2, 22) = 0.46$, $p = .64$. A significant main effect was found for target load, $F(1.4, 15.1) = 45.2$, $p < .001$. (Greenhouse–Geisser adjustment for the violation was sphericity.) Follow-up post hoc tests were performed with a Bonferroni adjustment for multiple comparisons. Normalized CE was greater at 120% ($M = 7.3\%$, $SD = 2.1$) than 140% ($M = 3.6\%$, $SD = 2.3$) and 160% ($M = 0.46\%$, $SD = 2.2$), $p < .001$, and normalized CE was greater at 140% than 160%, $p < .001$ (Figure 5).

Discussion

The purpose of this study was to investigate force sense at the shoulder. We hypothesized that there would be a decrease in error for force sense as elevation angle and external load increase, as was previously observed in JPS. The results from CE partially support our hypothesis, with decreasing CE with increasing load observed in both absolute and normalized data (Figures 3 and 5). An effect of angle was observed in the absolute RMS data with increased error at 90° compared with 50°. This is opposite to the angle effect that was observed for JPS at the shoulder. However, when the RMS error is normalized to target torque, the angle effect is no longer significant.

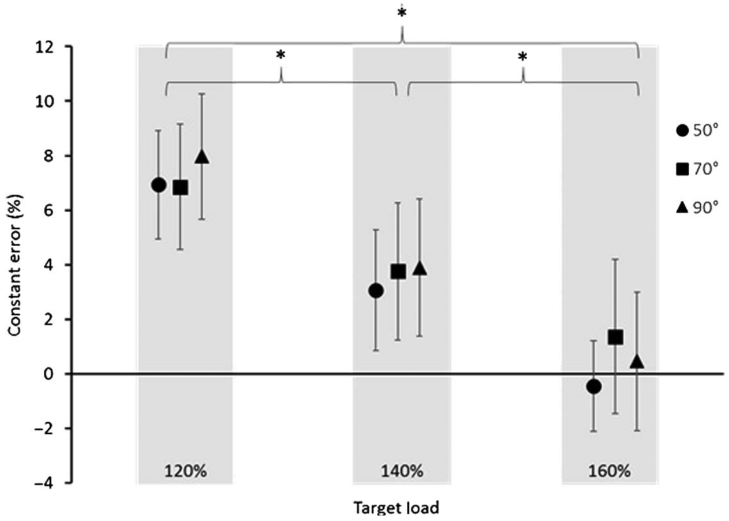

Figure 5 — Normalized constant error for each target load and angle. The main effect for load was significant, $p < .001$. Follow-up t tests found that the difference between each load condition was statistically significant, $p < .001$. *Statistically significant difference between loads.

For the significant effect of target load in CE, a decrease in CE when load was increased, we observed that the number of subjects who tended to undershoot the target increased as the target load increased. As CE shows directional bias, a mix of negative and positive values that are averaged could result with a number closer to the target than their absolute values scores actually were. This is why the CE approaches zero for the 160% target load. The effect of load was absent in both absolute and normalized RMS error data. Although load affects the directionality of errors, it does not affect accuracy.

There was a significant effect of angle on absolute RMS errors, with an increase in error as angle increase for all loads (Figure 2). However, when the RMS error data were normalized to a percentage of the target load, the effect was no longer observed (Figure 4). Absolute force sense accuracy depends on the load experienced. These results are indicative of a decrease in accuracy that corresponds to the increase in torque experienced by the upper extremity at each elevation angle. These findings were also observed in the ankle, where decreased accuracy was also observed with increased load (Docherty & Arnold, 2008; Docherty et al., 2004).

These results also do not agree with force sense studies at other joints. In the ankle studies that did show that as load increases, force sense accuracy decreases (Docherty & Arnold, 2008; Wright & Arnold, 2012), the data were not normalized. Therefore, it is uncertain if the error is proportional to the target load in these studies. Future research investigating force sense of the upper extremity should examine the data from both absolute and normalized perspectives, as error may increase as a function of target load. However, these results do agree with those at the index finger where subjects tended to overshoot the target at low force levels (Walsh et al., 2011) but not with the ankle where subjects overshot the target more at higher loads (Dos Santos Haupenthal et al., 2015). These direct comparisons with other force sense studies at different joints should be interpreted with caution. Although all of these studies used an ipsilateral force reproduction protocol, there was still substantial difference in the methodology including number of repetitions, target loads, memorization time, and joint angle.

Our results show that CE improved with load, but accuracy did not. This indicates that subjects became more inconsistent with the direction of their error but not more or less accurate. This may reflect possible noise in the system, where subjects are accurate within a certain bandwidth. The available information in force sense may be less than is available during active JPS. As muscle spindle signals are potentially filtered out (McCloskey et al., 1983), the amount of information and the manner in which the information is interpreted by the central nervous system may be different.

From our current dataset, we can conclude that the effect of angle on shoulder force sense behavior is different from shoulder JPS, where both CE and accuracy improved with increased humeral elevation (King et al., 2013; Suprak et al., 2006). The differing behavior between JPS and force sense may be a contributing factor as to why a correlation has not yet been found between them at any joint (Docherty et al., 2004; Kim et al., 2014; Li et al., 2016).

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