Central fatigue mechanisms are responsible for decreases in hand proprioceptive acuity following shoulder muscle fatigue

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ARTICLE INFO

ABSTRACT

Muscle fatigue is a complex phenomenon, consisting of central and peripheral mechanisms which contribute to local and systemic changes in motor performance. In particular, it has been demonstrated that afferent processing in the fatigued muscle (e.g., shoulder), as well as in surrounding or distal muscles (e.g., hand) can be altered by fatigue. Currently, it is unclear how proximal muscle fatigue affects proprioceptive acuity of the distal limb. The purpose of the present study was to assess the effects of shoulder muscle fatigue on participants' ability to judge the location of their hand using only proprioceptive cues. Participants' ($N = 16$) limbs were moved outwards by a robot manipulandum and they were instructed to estimate the position of their hand relative to one of four visual reference targets (two near, two far). This estimation task was completed before and after a repetitive pointing task was performed to fatigue the shoulder muscles. To assess central versus peripheral effects of fatigue on the distal limb, the right shoulder was fatigued and proprioceptive acuity of the left and right hands were tested. Results showed that there was a significant decrease in the accuracy of proprioceptive estimates for both hands after the right shoulder was fatigued, with no change in the precision of proprioceptive estimates. A control experiment ($N = 8$), in which participants completed the proprioceptive estimation task before and after a period of quiet sitting, ruled out the possibility that the bilateral changes in proprioceptive accuracy were due to a practice effect. Together, these results indicate that shoulder muscle fatigue decreases proprioceptive acuity in both hands, suggesting that central fatigue mechanisms are primarily responsible for changes in afferent feedback processing of the distal upper limb.

1. Introduction

Muscle fatigue, defined as exercise-induced impairment of motor performance (Enoka & Duchateau, 2008), is a topic of interest in the field of motor control. While muscle fatigue typically arises during intense physical activity and sustained physical efforts, it can be induced in a laboratory environment using a variety of different protocols; these include (but are not limited to) maximum effort contractions, prolonged isometric contractions, or repetitive contractions performed over time. In general, the multiple internal mechanisms which contribute to the development of fatigue can be categorized into two broad types: peripheral mechanisms, measured as reductions to the intramuscular functions of a specific muscle or muscle groups (i.e., reduction of voluntary force capacity), and central mechanisms, measured as reductions in neuromuscular propagation, voluntary activation, modifications to processing afferent or efferent information, or schematic changes to how a movement is performed (Barry & Enoka, 2007; Carroll,

Taylor, & Gandevia, 2017; Emery & Côté, 2012; Enoka & Duchateau, 2008; Halperin, Chapman, & Behm, 2015; Halson, 2014; Martin & Rattey, 2007; Vøllestad, 1997). In combination, these fatigue mechanisms have been shown to be responsible for modifications to the timing of motor neuron recruitment, kinematics underlying movement execution, muscle coordination, and a muscle's voluntary force capacity (Cowley & Gates, 2017; Emery & Côté, 2012; Halson, 2014; Huffenus, Amarantini, & Forestier, 2006; Srinivasan, Sinden, Mathiassen, & Côté, 2016).

Muscle fatigue has also been identified as one of the main contributors to changes in upper limb kinematics in repetitive workplace activities and athletic performance. The joints that create the human shoulder allow the upper limb to have a large functional range (Veeger & van der Helm, 2007); the proximal joints are responsible for gross and stabilizing movements of the limb, and the distal joints are responsible for fine and specific movements required by the hand during upper limb motor tasks (Cowley & Gates, 2017). The quality of movement performed by the joints proximal to the wrist can have an effect on the performance of the hand. For example, the glenohumeral joint must flex or abduct over 90° in order for an individual to raise their hand above their head. Thus, any motor impairment, pain, or fatigue of the muscles controlling the actions performed at the glenohumeral joint could affect position sense and/or resulting movements at the distal joints. In accordance with this suggestion, Zabihhosseinian, Holmes, and Murphy (2015) reported fatigue of the cervical extensor spinae muscles, induced with a submaximal isometric fatigue protocol, increased absolute elbow joint position errors when assessed with an active repositioning task. Furthermore, Vafadar, Côté, and Archambault (2012) reported shifts in position sense of the upper extremity following upper limb fatigue.

However, it is still possible to perform actions accurately in fatigued states. During multi-joint movements, the central nervous system (CNS) adapts to fatigue by compensating for any changes in performance in order to preserve accuracy (Côté, Mathieu, Levin, & Feldman, 2002; Côté, Raymond, Mathieu, Feldman, & Levin, 2005; Emery & Côté, 2012; Huffenus et al., 2006). For example, Huffenus et al. (2006) found no differences in hand (end point) trajectories during a disc-tossing task between two groups after undergoing either a proximal muscle (triceps brachii) or a distal muscle (extensor digitorum) fatigue protocol; however, there were changes to the coordination and muscle activation patterns of the muscles as measured by electromyography (EMG). Similarly, Côté et al. (2002) found that the upper limb was able to maintain endpoint trajectory in a fatigued state due to motor compensations while elbow muscle fatigue contributed to decreased motion amplitude at the elbow during a sawing movement. Furthermore, Emery and Côté (2012) reported that participants maintained upper limb endpoint (right hand) accuracy assessed via an active finger-to-target position sense task after performing a repetitive pointing task to fatigue. Again, the researchers attributed the maintenance of proprioceptive acuity to increased activation of non-fatigued muscles; specifically, that compensatory changes at the elbow joint helped participants maintain upper limb endpoint (hand) accuracy (Emery & Côté, 2012).

A review of the literature reveals that research examining the effects of fatigue on proprioceptive acuity of distal joints has typically employed an active repositioning task (Goble & Brown, 2009). It is unclear if proprioceptive acuity would be maintained following fatigue in a passive positioning task where motor compensation was not possible. The current study looked to determine if proximal shoulder muscle fatigue affects proprioceptive acuity of the distal hand when assessed with a passive protocol, thus removing active compensation or voluntary, goal-directed movement. We further probed if the potential influence of fatigue is driven by peripheral (local, intramuscular) versus central (non-local, neural) fatigue mechanisms. To address these questions, proprioceptive acuity of the right and left hands were tested in a perceptual judgement task in which participants verbally indicated the position of their hand relative to a visual reference target. The reference targets were located 10 cm (near) and 20 cm (far) from a starting position. On each trial, the hand was passively moved into position by a robot manipulandum. Proprioceptive acuity of both limbs was assessed before and after a fatigue protocol, in which participants performed a low force, low velocity repetitive pointing task in the horizontal plane to tire the shoulder muscles of the right arm. Similar fatiguing tasks have been used in previous studies, and have been shown to have a longer recovery time than isometric contractions (Baker, Kostov, Miller, & Weiner, 1993; Emery & Côté, 2012; Sterner, Pincivero, & Lephart, 1998; Zabihhosseinian et al., 2015). We hypothesized that shoulder muscle fatigue would lead to a decrease in proprioceptive acuity in the right hand when assessed in a passive task, as muscle compensation for local and non-local muscle fatigue could not occur. Any effects observed in the left hand when the right shoulder was fatigued would suggest that central fatigue mechanisms contribute to changes in proprioceptive acuity.

2. Methods

2.1. Participants

Sixteen healthy, right-handed adults (8 female; mean age = 23.5, SD = 2.8) were recruited to participate in this study. Handedness was confirmed with the Edinburgh Handedness Inventory self-report questionnaire (mean score = 82%, SD = 0.2; Oldfield, 1971). All participants reported no history of neurological or motor dysfunction and had normal or corrected-to-normal vision. Participants provided informed consent prior to the first session, and testing was conducted in accordance with the ethical guidelines set by the University of Ottawa's Office of Research Ethics and Integrity.

2.2. Experimental design

Each of the 16 participants completed 2 experimental sessions separated by a minimum of 1 day (mean = 7.3 days, SD = 6.2). Both experimental sessions were divided into 3 testing blocks, which were performed in the same order: a proprioceptive estimation task (PreFT), a repetitive pointing task performed to fatigue (FT), and another proprioceptive estimation task (PostFT). The order that participants performed the experimental sessions was randomized such that half of the participants began with a session testing
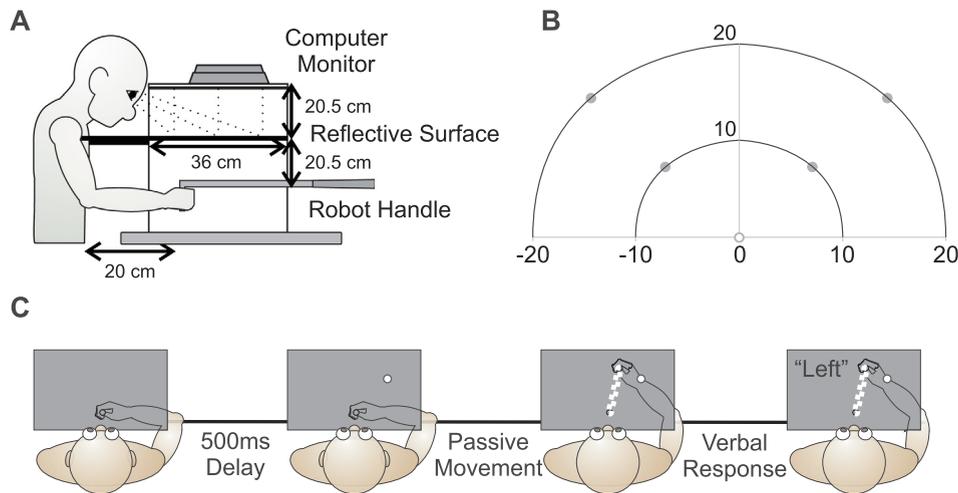
Fig. 1. A. Lateral view of the experimental set-up for the proprioceptive estimation task. B. The home position (0,0), and the four reference targets (right and left near (10 cm), and right and left far (20 cm)) around which participants made their proprioceptive estimates. C. Example trial in the proprioception estimation task.

proprioceptive acuity of the left hand while performing the FT with their right arm, and the other half began with a session in which only the right arm was tested in all tasks.

2.3. Proprioceptive estimation task

The PreFT and PostFT proprioceptive estimation trials were performed with the participant seated at a table. Participants' distance from the table and the height of their chair were adjusted, measured, and marked to ensure they were in a similar position for the PreFT and PostFT proprioception estimation trials. Participants were instructed to grasp the vertical handle of a KINARM robot manipulandum (Bkin Technologies Ltd., Kingston, Canada) with their testing hand. As shown in Fig. 1A, a monitor was mounted horizontally above the participant's hand, and positioned to be in line with their forehead. This monitor projected visual stimuli onto a reflective surface which was positioned halfway between the participant's forehead and robot manipulandum. Thus, participants perceived the visual stimuli to be in the same plane as their hand when they were holding the robot handle. The room lights were turned off and a cloth barrier was draped between the experimental apparatus and participant to ensure they could not see their arms at any point during the task.

At the beginning of each proprioception estimation trial, the robot handle was positioned directly under the home position, indicated by a white circle (diameter = 1 cm) and displayed on the reflective surface so that it was visible to the participant (Fig. 1B). The handle was held at this home position for 500 ms. Following 500 ms, the white circle disappeared, and the robot handle moved the participant's hand out until it was the same distance from the home position as one of the four reference targets (movement time = 1500 ms). The reference target appeared once the hand had finished moving. Participants then made a two-alternative forced-choice judgment about the position of their hand, indicating whether their hand was left or right of the reference target. There were no time constraints during the task and participants were encouraged to take as long as they needed before verbally indicating to the experimenter whether their hand was to the left or to the right of the reference target (Fig. 1C). Once the participant's answer was recorded, the reference target disappeared and the robot handle moved the participant's hand back to the home position for the next trial. There were no goal-directed movements performed by participants throughout the proprioception estimation trials. If participants attempted to move the robot handle, a resistance force [proportional to the depth of penetration with a stiffness of 2 N/mm and a viscous damping of 5 N/(mm/s)] was generated to resist their movement(s) (Cressman & Henriques, 2009).

The passive positioning by the robot handle with respect to each of the reference targets was adjusted over trials using an adaptive staircase algorithm (Cressman & Henriques, 2009; Kesten, 1958; Treutwein, 1995). Each reference target had a left and a right adaptive staircase, consisting of 25 trials each, which were presented in a random order. Each staircase began with the robot handle positioned either 20° to the left or to the right of a reference target (along a circular arc, at the same distance as the reference target from the home position (Fig. 1B)), and that angle would change for a given staircase depending on a participant's response. If the participant responded consistently, the left and right staircases converged to a point at which the participant had an equal probability of reporting that their hand was to the left or to the right of the reference target, and thus indicating the position at which the participant perceived their hand to be aligned with the reference target (Cressman & Henriques, 2009). 200 trials (50 per reference target) were completed in each of the PreFT and PostFT tasks. A participant's right arm was tested on one testing day and the left arm was tested on a separate day, and the order in which the arms were tested was counter-balanced across participants.

2.4. Fatiguing task

A repetitive pointing task was used as the fatiguing task (FT) to fatigue the shoulder muscles. This task, adopted from Emery and Côté (2012), has been shown to induce shoulder muscle fatigue, confirmed via increased shoulder muscle activity measured by surface EMG, as well as changes to the muscle activities of postural muscles (Emery & Côté, 2012; Fuller, Lomond, Fung, & Côté, 2009). Participants performed the FT in the room adjacent to where the proprioception estimation trials were performed. The FT began within a few minutes of the PreFT task and immediately before the PostFT task. The FT was performed with the right arm in both experimental sessions. Two targets were placed in front of the participant; one at 30% and the other at 100% of their measured arm length. Both targets were positioned at the height of the participant's shoulders and aligned with their midline. Participants were to stand comfortably with their feet shoulder-width apart and their left arm hanging at their side. Participants then held out their right arm in front of them at approximately 90° of shoulder flexion and, at a beat of one movement per second (1-Hz), tapped between the two targets with their index finger while maintaining 90° of shoulder flexion and abduction. A metronome was provided to assist with the prescribed rhythm (Metronome – iPhone app, Uwe Hollatz). Similar to the instructions of Emery and Côté (2012), participants were instructed to "perform the task as comfortably and naturally as possible for as long as possible."

At one-minute intervals throughout the FT, participants were asked to rate their perceived level of exertion of their shoulder muscles on a Borg CR10 scale (Haddad et al., 2013; Noble, Borg, Jacobs, Ceci, & Kaiser, 1983). Participants continued the FT until one of the following stoppage criteria were met: a rating of perceived exertion (RPE) of 8 or higher was reported, the 1-Hz movement frequency could not be maintained, or the participant had performed the task for more than 20 min. Similar stoppage criteria have been used previously and have demonstrated an association with objective signs of muscle fatigue (reduction in force output and changes in EMG frequency) (Cowley & Gates, 2017; Emery & Côté, 2012; Fuller et al., 2009). Participants were verbally encouraged throughout their performance; however, they were unaware of the stoppage criteria and were not provided with any feedback regarding their performance at any point during or after the FT. Immediately after the completion of the FT, and while holding their right arm at 90° shoulder abduction and 90° elbow flexion, participants returned to the adjacent testing room to begin the PostFT proprioception estimation trials. All PostFT trials began within 1 min of completion of the FT.

3. Data analyses

In the FT, participants' RPE over time, total completion time, and reason for stopping were recorded. The mean performance RPE across time and mean time to fatigue were calculated across all participants.

For the PreFT and PostFT, the position of the robot handle and participants' proprioceptive estimates were collected with the Dexterit-E operating software (Bkin Technologies Ltd., Kingston, Canada). A logistic function was fitted to each participant's responses for each reference target. Based on each logistic function, we calculated the bias (point corresponding to a participant responding left (or right) 50% of the time) and uncertainty (the difference between the values at which the response probability was 25 and 75%). Bias is a measure of the accuracy of hand-reference target alignment, and the magnitude of the uncertainty range defines its precision. The steeper the logistic function, the smaller the range of uncertainty and hence the less distance a participant's hand had to change before the participant was confident (and hence more consistent in their responses) about their hand's position relative to the reference target (Cressman & Henriques, 2009; Henriques & Soechting, 2003). A participant's bias and precision (or, uncertainty range) were calculated for each reference target for the left and the right hands both before and after the FT.

Statistical analysis was conducted using SPSS software. Paired-samples T-tests were used to determine if there were differences in mean performance RPE and time to fatigue for participants across the two experimental sessions. Further, T-tests were conducted to assess for differences in average RPE and time to fatigue across the two experimental sessions between female and male participants. Participants' bias data (in degrees and centimeters) and uncertainty range data (in degrees and centimeters) were analyzed in a 2 Time (PreFT and PostFT sessions) × 2 Hand (right and left) × 2 Distance (near and far reference targets) × 2 Location (right and left reference targets) repeated measures analysis of variance (RM-ANOVA). Differences with a probability of < 0.05 were considered significant. Following a significant interaction, a simple effect analysis was conducted. All post-hoc tests were conducted using Bonferroni corrections.

4. Results

4.1. Fatiguing task

An RPE score was collected every minute during the performance of the fatiguing protocol for each participant. Fig. 2 presents the changes in RPE over time for each participant in each of the two testing sessions. Overall, the mean time to fatigue was 6.09 min (3.70 SD) and the mean task RPE was 5.00 (0.55 SD). The majority of FT performances (29 of 32) were terminated due to a participant reporting an RPE of 8 or higher out of 10. These values are similar to previous reports in which most participants reached the stop criteria of reporting an RPE of 8 or higher in approximately 7 min (Emery & Côté, 2012; Fuller et al., 2009). One participant performed the pointing task to the 20-min limit on the second day of testing, and two performances from separate participants were terminated due to volitional exhaustion (one at 6.12 min, another at 2.52 min; last RPE recorded was 7). Most participants were consistent in their performance over the two experimental sessions. Paired-samples t-tests revealed no significant differences between average session RPE (t (15) = 1.962, $P = 0.069$) or time to fatigue (t (15) = 1.182, $P = 0.256$) across testing sessions. Fig. 3 presents the relationship between Time to Fatigue in the first testing session and Time to Fatigue in the second testing session. The data points
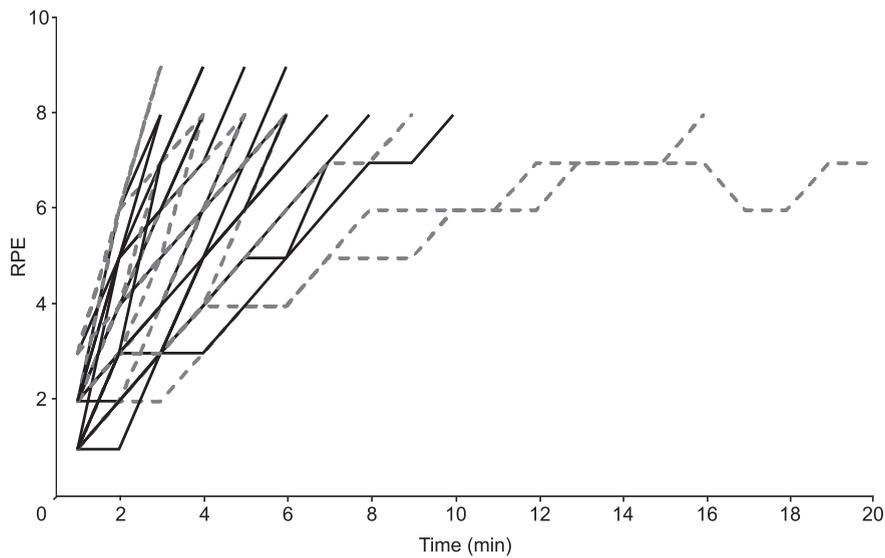
Fig. 2. Rating of Perceived Exertion (RPE) reported by each participant at every minute of performance of the FT. Black lines correspond with a participant's RPE in the first experimental session, and dashed lines indicate performance in the second experimental session.
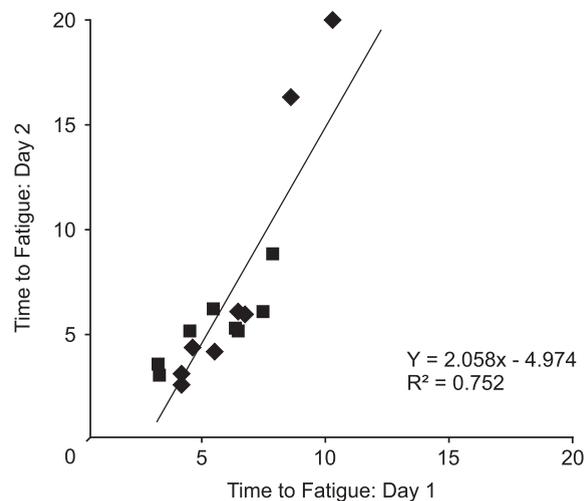

Fig. 3. Each data point represents a participant's time to fatigue on Day 2 relative to their time to fatigue on Day 1. The male participants are represented as black squares, and the female participants are represented as black diamonds.

are coded to represent sex, with squares representing male participants and diamonds representing female participants. For the females, their mean RPE was 4.88 (0.52 SD) and their mean time to fatigue was 6.90 min (4.89 SD). For the males, their mean RPE was 5.13 (0.56 SD) and their mean time to fatigue was 5.28 min (1.73 SD). T-tests revealed no significant differences between male and female average RPE (t (15) = 1.858, P = 0.083) or time to fatigue (t (15) = 1.309, P = 0.210).

4.2. Proprioception estimation task

The mean proprioceptive biases for right and left arm performance both prior to and after the FT are presented in Fig. 4A and B, respectively. The proprioceptive biases of each participant were analyzed in both degrees and centimeters. RM-ANOVA(degrees) revealed a significant main effect of Hand, indicating that proprioceptive biases were different between the left and right hands ($F_{(1, 15)}$ = 36.681, P < 0.001). Generally, participants perceived their right hand to be aligned with the reference target when it was slightly to the left of the target (Fig. 4A), and participants perceived their left hand to be aligned with the reference target when it was slightly to the right of the target (Fig. 4B). While the main effects of Time ($F_{(1, 15)}$ = 0.103, P = 0.753), Distance ($F_{(1, 15)}$ = 0.281, P = 0.604), and Location ($F_{(1, 15)}$ = 0.049, P = 0.827) were not significant, analysis revealed a significant Hand × Time interaction ($F_{(1, 15)}$ = 9.046, P = 0.009). Post-hoc analysis showed that proprioceptive biases were less accurate in both the left (P = 0.022) and the right (P = 0.036) hands after the FT. Specifically, the PostFT proprioceptive biases for the left hand were 1.56°
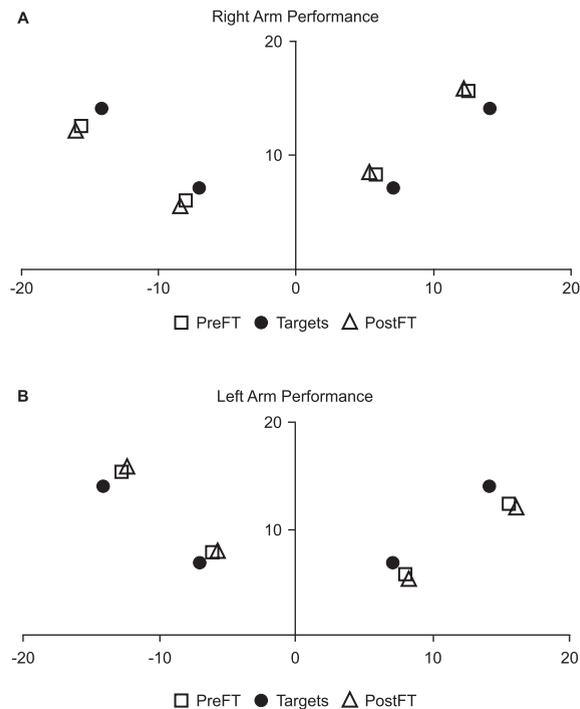
Fig. 4. A. Mean proprioceptive biases when performing the proprioceptive estimation trials with the right arm. B. Mean proprioceptive biases when performing the proprioceptive estimation trials with the left arm. The circles represent the reference targets, the squares represent the average proprioceptive biases in the PreFT trials, and the triangles represent the average proprioceptive biases in the PostFT trials.

(SD = 2.43) further to the right than the PreFT proprioceptive biases, and the right hand biases were 1.83° (SD = 3.19) further to the left. A paired samples *t*-test revealed that the magnitude of the difference between the left and right hands was significant (t (15) = 0.993, *P* = 0.009), such that the right hand performed worse than the left hand after the right shoulder was fatigued. Additionally, there was a significant Hand × Distance interaction ($F_{(1, 15)}$ = 12.492, *P* = 0.003), with post-hoc analysis indicating that participants performed differently at the near and far reference targets with the right (*P* = 0.016) and left (*P* = 0.033) hands. Specifically, the right hand had a mean proprioceptive bias of −8.71° (SD = 8.94) at the near targets and −6.07° (SD = 5.79) at the far targets, with a mean difference of 2.64° (SD = 3.89). The left hand had a mean proprioceptive bias of 7.61° (SD = 7.19) at the near targets and 5.64° (SD = 4.48) at the far targets, with a mean difference of 1.98° (SD = 3.36). All other interactions were not significant (*P* > 0.05).

To understand the influence of distance on proprioceptive estimates, the biases at each reference target were converted from degrees into resultant distance from the target in centimeters. RM-ANOVA(cm) revealed a main effect of Time ($F_{(1, 15)}$ = 22.223, P < 0.001), suggesting again that participants' proprioceptive biases were further away from the reference targets after the fatiguing protocol (2.53 cm; SD = 1.29) compared to before the fatiguing protocol (2.04 cm; SD = 1.04). Furthermore, there was also a main effect of Distance ($F_{(1, 15)}$ = 88.626, P < 0.001), suggesting the proprioceptive biases were worse at the far reference targets (2.71 cm; SD = 1.29) than at the near reference targets (1.86 cm; SD = 1.01). All other interactions were not significant (*P* > 0.05).

With respect to uncertainty ranges, RM-ANOVA(degrees) revealed a significant main effect of Distance ($F_{(1,15)}$ = 82.248, P < 0.001). Participants had a greater uncertainty range (mean = 10.39°; SD = 2.79) at the near reference targets compared to the far reference targets (mean = 6.55°; SD = 2.12). When the uncertainty ranges were converted from degrees into centimeters, RM-ANOVA(cm) again revealed a main effect of Distance ($F_{(1,15)}$ = 18.935, P = 0.001), indicating that there was a larger uncertainty range at the far reference targets (mean = 2.28 cm; SD = 0.74) than at the near reference targets (mean = 1.81 cm; SD = 0.48). All other main effects for RM-ANOVA(degrees) and RM-ANOVA(cm) were not significant and there were no significant interactions (all P > 0.05).

4.3. Control experiment

A control experiment was conducted to determine if the decrease in participants' proprioceptive acuity from PreFT to PostFT was due to time, and thus independent from the fatigue protocol. 8 new participants (4 females; mean age = 23.9 years, SD = 2.7) performed the PreFT and PostFT proprioception estimation trials with their right hand before and after 10 min of quiet sitting. RM-ANOVA(degrees) of right hand proprioceptive biases revealed no significant main effects of Time ($F_{(1,7)}$ = 0.424, P = 0.536), Distance ($F_{(1,7)}$ = 2.066, P = 0.194), or Location ($F_{(1,7)}$ = 0.258, P = 0.627), and no significant interactions (P > 0.05). Similar results were attained when an analysis was completed with the results expressed in centimeters (P > 0.05). While ANOVA did not
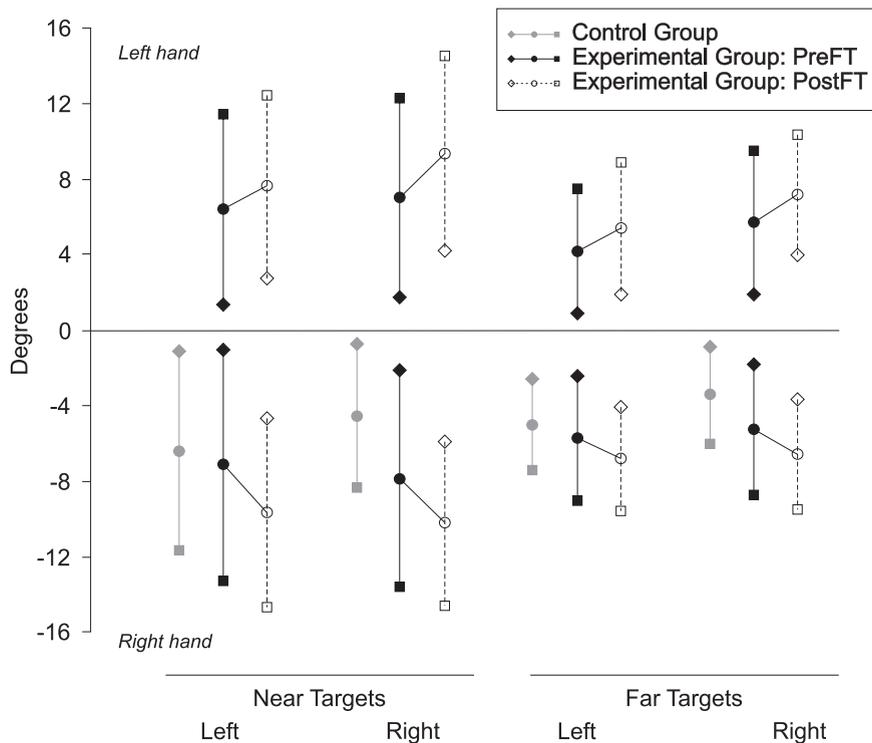
Fig. 5. Mean biases and precision (uncertainty range) measured in degrees at each reference target before (PreFT) and after (PostFT) the fatigue protocol, and Control conditions. Since there was no significant main effect of Time in the Control Group, their proprioceptive estimates are collapsed across PreFT and PostFT in this figure. The circles represent the 50% bias, the diamonds represent the 25% bias, and the squares represent the 75% bias of each target. The negative values represent a bias to the left of the target (the right hand), and the positive values represent a bias to the right of the target (the left hand).

reveal a significant difference between the far and near targets as found with the fatigued experimental group, biases were 1.3° less accurate at the near reference targets compared to the far reference targets, or 0.4 cm less accurate at the far reference targets compared to the near reference targets. With respect to uncertainty ranges, RM-ANOVA(degrees) again revealed a significant main effect of Distance ($F (1,7) = 25.628$, $P = 0.001$), indicating participants were less precise around the near reference targets (mean $= -9.16°$, SD = 3.04) than around the far reference targets (mean $= -5.03°$, SD = 1.91) (Fig. 5). These results are similar to those attained with the fatigued experimental group. However, the RM-ANOVA(cm) revealed no additional significant main effects or interactions (all P > 0.05). Final analyses looked to compare initial (i.e., PreFT) proprioceptive biases and uncertainty ranges in the right hand across the two groups of participants using a 2 Group (Experimental and Control) × 2 Distance (near and far reference targets) × 2 Location (right and left reference targets) mixed ANOVA, with RM on the last two factors. Proprioceptive biases and uncertainty ranges measured in both degrees and centimeters did not differ between groups, nor were there any group interactions (all P > 0.05).

5. Discussion

The purpose of the present study was to investigate the effects of proximal shoulder muscle fatigue on distal hand proprioceptive acuity. Proprioceptive acuity was assessed in a passive estimation task, eliminating goal-directed movements and the potential for compensatory muscle activation to influence results. Furthermore, as fatigue is a complex phenomenon, we attempted to differentiate between peripheral and central fatigue mechanisms by testing proprioceptive acuity of the left and right hands after fatiguing the right shoulder.

5.1. Muscle fatigue

Shoulder muscle fatigue developed gradually in our FT, manifesting as an increase in RPE as time progressed. The mean time to fatigue was just over 6 min. This time to fatigue is comparable to previous reports of mean time to fatigue in studies using a similar fatiguing protocol (Emery & Côté, 2012; Fuller et al., 2009). For the present study, the FT (adapted from Emery & Côté, 2012) was selected as it was a low force, low velocity, long duration fatigue protocol. We purposely choose this FT because submaximal exercise to fatigue tasks have been associated with a longer recovery period than tasks involving short duration, high intensity activities (i.e. maximum voluntary contraction (MVC) fatiguing protocols) (Baker et al., 1993; Halperin et al., 2015; Sterner et al., 1998). Indeed,

Carroll et al. (2017) reported that complete recovery from short duration MVC fatigue protocols can occur in as little as 30 s after the end of the exercise. In the current study, the recovery time was an important consideration for the fatigue protocol as we wanted peripheral and central mechanisms of fatigue to be present throughout the PostFT proprioception estimation trials, which lasted approximately 25 min.

5.2. Proprioceptive accuracy and fatigue

In line with previous work (Jones, Cressman, & Henriques, 2010; Wilson, Wong, & Gribble, 2010), we found proprioceptive biases in opposite directions when comparing across hands (Fig. 4). In other words, participants perceived their right hand to be at the reference target when it was slightly to the left of the target, indicating that participants typically felt their right hand to be more rightwards than it actually was. Likewise, participants perceived their left hand to be at the reference target when it was slightly to the right of the target, indicating that participants typically felt their left hand to be more leftwards than it actually was. While the biases at each hand were in opposite directions, participants' precision associated with these biases did not differ between the left and right hands. These findings are similar to ones previously reported using similar proprioceptive acuity protocols in non-fatigued states (Jones et al., 2010; Wilson et al., 2010). The mislocalization of both limbs in opposite directions has been suggested to arise due to a misrepresentation of hand location relative to the body's midline (Ghilardi, Gordon, & Ghez, 1995). Moreover, the bias patterns for the left and right hands observed in our proprioceptive estimation task are consistent with those reported in reaching tasks (van Beers, Sittig, & Denier van der Gon, 1998; Crowe, Keessen, Kuus, van Vliet, & Zegeling, 1987; Haggard, Newman, Blundell, & Andrew, 2000; Liu, Sexton, & Block, 2018). Specifically, these studies have reported that, when reaches are made to the right hand using the left hand, participants overestimate the horizontal location of the right hand, reaching too far to the right, and when reaches are made to the left hand using the right hand, participants overestimate the horizontal location of the left hand, reaching too far to the left. This pattern in reaching errors would be expected if participants truly misperceived the location of their right hand (or left hand) to be more to the right (or left) than its actual location.

With respect to the current question of interest, we found that proprioceptive biases for the left and right hands increased following the FT (i.e., became less accurate). Previous reports using similar passive proprioceptive acuity protocols have not examined nor demonstrated any change to proprioceptive acuity over time (Jones et al., 2010; Wilson et al., 2010; Wong, Wilson, & Gribble, 2011). Indeed, the control group in the present experiment did not demonstrate the same increase in proprioceptive biases as the experimental group; thus, the increase in proprioceptive biases for the left and right hands can be attributed to fatigue.

In the current study, shoulder muscle fatigue effected proprioceptive accuracy of both the left and right hands. Proprioceptive biases in the left hand were assessed to determine if the effects of fatigue could be attributed to more peripheral or central origins. To review, mechanisms of peripheral fatigue occur within a fatigued muscle or muscle groups, and central fatigue mechanisms occur within the CNS (Carroll et al., 2017; Enoka, 1995; Froyd, Beltrami, Millet, & Noakes, 2016; Gandevia, 2001). Studies have shown that the extent to which peripheral and central fatigue mechanisms contribute to reductions in a desired motor output may depend on the duration and intensity of the exercise performed leading to fatigue (Baker et al., 1993; Carroll et al., 2017; Enoka, 1995; Froyd et al., 2016). For example, Baker et al. (1993) concluded that fatigue effects measured after an exercise protocol lasting longer than a few minutes tend to be more central than peripheral in origin. Similarly, Froyd et al. (2016) reported that central fatigue primarily occurred during cycling time trials lasting greater than 10 min, whereas peripheral fatigue was predominant during time trials lasting 3 min or less. Furthermore, Teo, Rodrigues, Mastaglia, and Thickbroom (2012) reported that slower, less intense activities led to greater and more sustained depressions in corticomotor excitability after exercise.

In the present study, our results support the idea that central fatigue mechanisms play a role during long duration, low intensity activity (mean time to fatigue = 6.09 min), as proprioceptive estimates were less accurate in both hands following a repetitive pointing task performed until fatigue by the right hand. Interestingly, we found differences in the magnitude of changes in proprioceptive estimates in the left and right hands following right shoulder fatigue, such that a greater change was seen in the right hand in the PostFT trials compared to the left hand. These results suggest that right shoulder fatigue, although affecting proprioceptive acuity in both hands, affected the hand of the fatigued limb slightly more than the contralateral hand. As multiple processes contribute to muscle fatigue, this effect could be due to the addition of peripheral fatigue mechanisms occurring within the muscles of the right arm, along with the present central fatigue mechanisms.

5.3. Proprioceptive precision and fatigue

While the FT led to less accurate proprioceptive biases, we found no differences in uncertainty ranges (or variability of responses) across time (i.e., PreFT versus PostFT trials). There was an influence of reference target distance on uncertainty range. Specifically, participants in the fatiguing protocol were less precise in their proprioceptive estimates at the far targets compared to the near targets (when measured in centimeters) during both the PreFT and PostFT, and, while not statistically significant, participants in the control experiment demonstrated a similar decrease in precision with greater target distance.

The precision of proprioceptive estimates provides insight into the variability of participants' proprioceptive responses, as a greater uncertainty range corresponds to a greater inconsistency in responses at a given reference target (i.e., participants were not as confident regarding their hand's position relative to a given reference target). To our knowledge, there is a limited amount of research that has assessed proprioceptive variability at different target distances. Speculatively, one of the reasons for the larger inconsistency in participant's responses regarding proprioceptive positions found in the present experiment at the far targets could have to do with the time it took for the robot handle to move the hand into position, and hence the speed the hand was moving at.

The manipulandum moved from its start to end position for each target (near and far targets) in 1500 ms; thus, the robot handle actually had a faster velocity for the far targets than the near targets. This difference in passive positioning speed of the participants' hands may have contributed to proprioceptive acuity. In support of this suggestion, Goble and Brown (2009) have shown less accurate proprioceptive acuity when assessed in active position tasks performed at faster movement speeds. Additionally, Brown, Rosenbaum, and Sainburg (2003) have reported that faster movements tend to result in a quicker rate of limb position drift when movements are solely guided by proprioception (no vision). Finally, Djupsjöbacka and Domkin (2005) found that variable error (VE) was positively correlated with "movement extent", meaning the authors reported an increase in variability during active and passive limb-position matching tasks when the participants were required to match a joint angle that was farther away from their starting position. In other words, the further a participant was from their reference position, the larger their variability in performance (Djupsjöbacka & Domkin, 2005). Additionally, the same authors reported a larger difference in velocity-discrimination at a higher speed (50°/s) than at a lower speed (30°/s) during a passive upper limb velocity-discrimination task (Djupsjöbacka & Domkin, 2005). Given that we did not manipulate movement time (and hence speed) with reference target positions, future research is required to establish the influence of movement speed on proprioceptive acuity measured in passive positioning tasks.

5.4. Proprioceptive estimation task

A major difference in the present study from previous work investigating proprioceptive acuity and muscle fatigue is that a passive proprioceptive estimation task was used to assess proprioceptive acuity, in which participants made perceptual judgments regarding their limb's position relative to a reference target. A passive task eliminates goal-directed movements, effectively removing most efferent activity from the muscles in the upper limb while testing static position sense of the hand (Capaday, Darling, Stanek, & Van Vreeswijk, 2013; Hoseini, Sexton, Kurtz, Liu, & Block, 2015). The few studies that have examined the influence of fatigue on proprioceptive acuity with a passive repositioning task have shown that glenohumeral proprioceptive acuity decreases after a shoulder muscle fatigue protocol (Carpenter, Blasier, & Pellizzon, 1998; Voight, Hardin, Blackburn, Tippett, & Canner, 1996). Alternatively, active positioning tasks have tended to demonstrate that distal proprioceptive acuity is maintained following fatigue of the proximal limb (Emery & Côté, 2012). It has been suggested that position sense or movement accuracy is maintained following fatigue in these active tasks due to motor compensation from the non-fatigued muscles. Indeed, we are still able to perform accurate upper limb movements when the shoulders muscles are fatigued due to distal muscles compensating for changes at proximal joint(s) (Côté et al., 2002; Emery & Côté, 2012; Huffenus et al., 2006). The current study design allows us to draw conclusions regarding the effects of proximal shoulder muscle fatigue on distal hand proprioception when motor compensation cannot arise.

The current study also provides insight into changes in proprioceptive acuity when assessed in a visual-proprioceptive matching task. While typical proprioceptive acuity tasks have participants match or reproduce a reference limb position defined by proprioception, we had participants estimate the position of their hand relative to a visual reference target. A study conducted by Vafadar et al. (2012) also found changes in upper limb proprioceptive acuity in a visual-proprioceptive matching task following fatigue. Vafadar et al. (2012) investigated position sense of the upper limb using an active end-point position task before and after fatiguing the same limb. In their study, participants were asked to perform a visual-proprioceptive matching task by placing a block on a remembered visual position. The authors reported that proprioceptive accuracy changed in the vertical direction after the limb was fatigued (Vafadar et al., 2012). Vafadar et al. (2012) also found increases in proprioceptive variability after the fatigue protocol. The authors attributed these changes to a potential increase in participants' sense of effort to move their arm against gravity to match the remembered target position (Vafadar et al., 2012). In the present study, accuracy of proprioceptive estimates was shown to change in the horizontal plane (not the vertical plane as shown by Vafadar et al. (2012)) following fatigue, and fatigue did not have an effect on proprioceptive variability. In our design, gravity would have had little influence on participants' responses, as movements were made in a horizontal plane, with the hand placed into position by the robot manipulandum. Additionally, we limited motion of the upper limb, and did not allow participants' hands to vary in the vertical (near-far) direction with respect to a given reference target. Speculatively, significant changes in the vertical direction could have occurred between our PreFT and PostFT proprioceptive estimates, as shown by Vafadar et al. (2012); however, this was not examined in the present study. Together, our study and the results of Vafadar et al. (2012) demonstrate that proprioceptive acuity changes can be detected in visual-proprioceptive matching tasks, that do not require participants to remember a given proprioceptive position or process proprioceptive information related to both limbs (Goble, 2010).

6. Further direction/clinical considerations

Our interest lies in the motor control mechanisms surrounding fatigue, especially given that repetitive fatiguing tasks have been associated with an increased risk for injury (Halson, 2014; Nussbaum, 2001; van der Windt et al., 2000). Fatigue studies often include surface EMG as a diagnostic tool for measuring and evaluating muscle contractions, as it is a useful tool for investigating changes in neuromuscular activity of agonist, antagonist, postural and/or joint stabilizing muscles in various conditions (Cifrek, Medved, Tonković, & Ostojić, 2009; Emery & Côté, 2012). While EMG was not used in the present study, we are confident participants were fatigued after the FT based on the majority of participants reporting 8/10 on an RPE scale. However, EMG can provide instant data on the neural activity occurring within a specific muscle, and thus can be a useful tool for investigating for physiological changes related to fatigue (Cifrek et al., 2009). Blood lactate concentrations and heart rate data are other common measurements of physiological fatigue in sport environments and can provide further insight into the effects of fatigue mechanisms on performance (Cifrek et al., 2009). In the present study, only RPE was used to measure fatigue. In future research, it may be interesting to also collect EMG, blood

lactate, and heart rate data to further understand the relationship between physiological indicators of fatigue and changes in proprioceptive acuity.

7. Conclusion

The goal of the present study was to assess the effects of shoulder muscle fatigue on participants' ability to judge the location of their hand using only proprioceptive cues. We found that right shoulder muscle fatigue had an effect on accuracy of proprioceptive estimates of the left hand and the right hand when assessed in a passive task; thus, we conclude that central fatigue mechanisms are predominately responsible for changes in proprioceptive acuity of the hand following shoulder muscle fatigue.

Funding

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