Sex-Specific Links in Motor and Sensory Adaptations to Repetitive Motion–Induced Fatigue

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The objectives of this study were to assess the sex-specific relationships between motor and sensory adaptations to repetitive arm motion–induced neck/shoulder fatigue, and to measure how additional sensory stimulation affects these adaptations. Twenty-three participants performed two sessions of a repetitive pointing task until scoring 8 on the Borg CR10 scale for neck/shoulder exertion or for a maximum of 45 min, with and without sensory stimulation (i.e., light touch) applied on the fatiguing shoulder. Just before reaching the task termination criteria, all participants showed changes in mean and variability of arm joint angles and experienced a fivefold increase in anterior deltoid sensory threshold in the stimulus-present condition. Women with the greatest increases in anterior deltoid sensory thresholds demonstrated the greatest increases in shoulder variability ($r = .66$), whereas men with the greatest increases in upper-trapezius sensory thresholds demonstrated the greatest changes in shoulder angle ($r = -.60$) and coordination ($r = .65$) variability. Thus, sensory stimulation had no influence on time to termination but affected how men and women differently adapted, suggesting sex differences in sensorimotor fatigue response mechanisms.

Keywords: biomechanics, gender, motor control, muscle fatigue

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Muscular fatigue is a natural and daily occurring phenomenon, which is associated with many changes to an individual's physiology. Muscular fatigue is described as a temporary decrease in the ability to produce maximal force, accompanied by an increased level of perceived exertion (Enoka & Stuart, 1992). This phenomenon is associated with physiological consequences for motor and sensory systems across the entire body. Muscular fatigue has been associated with altered motor drive toward the muscle (Di Lazzaro et al., 2003), decreased force-generating capacity and decreased speed of muscular contraction (Bigland-Ritchie, Johansson, Lippold, & Woods, 1983), and heightened activity of sensory metaboreceptors and the fusimotor system (Amann, 2012). In addition, during the development of muscular fatigue, individuals have been found to adopt posture and movement changes that are specific to the kind of fatiguing motor task performed (Côté, Mathieu, Levin, & Feldman, 2002; Côté, Raymond, Mathieu, Feldman, & Levin, 2005; Forestier & Nougier, 1998; Fuller, Lomond, Fung, & Côté, 2009).

Moreover, different kinds of fatigue protocols have led to increases in motor variability (Cowley, Dingwell, & Gates, 2014; Fuller et al., 2009; Gates & Dingwell, 2011; Qin, Lin, Faber, Buchholz, & Xu, 2014). Motor variability, defined as the intrinsic variability in actions controlled by the sensorimotor system (Madeleine, 2010; Mathiassen, Möller, & Forsman, 2003), has evolved into an important concept in the field of biomechanics because of the proposed benefit of variability toward decreasing the rate of fatigue development and the relative risk of injury (Côté, 2014; Madeleine, 2010; Srinivasan & Mathiassen, 2012). However, the mechanisms underlying changes in motor variability remain poorly understood (Cantu, Emery, & Côté, 2014; Fuller, Fung, & Côté, 2013; Huysmans, Hoozemans, van der Beek, de Looze, & van Dieen, 2008; Missenard, Mottet, & Perrey, 2008).

Sensory signals arising from the site of a muscle are important for proprioception and therefore movement planning (Haggard, Taylor-Clarke, & Kennett, 2003). However, the effects of muscular fatigue on this branch of the sensorimotor system have not been as well explored as those on the motor system. Quantitative sensory threshold testing of cutaneous sensitivity to touch is one tool by which the state of the sensory system has been assessed (Arezzo et al., 1993). In the context of fatigue, Han, Park, Jung, Choi, and Song (2015) found decreases of cutaneous sensitivity in a test of two-point distinguishability. These findings were interpreted as evidence of impaired detection, signaling, and/or altered central processing resulting from fatigue, warranting more studies to shed light on this question.

Previous research has shown that changes in the sensory system have consequences on aspects of motor performance. For instance, altered sensory signaling resulting from fatiguing the plantar flexors has been observed to influence postural control (Hlavackova & Vuillerme, 2012; Vuillerme, Pinsault, & Vaillant, 2005), whereas providing additional sensory information through ankle support or light touch of an external stable object has been shown to rectify the negative effects of sensory deprivation on postural sway (Franzén, Gurfinkel, Wright, Cordo, & Horak, 2011; Kimura, Kouzaki, Masani, & Moritani, 2012). Therefore, it is conceivable that the decreased acuity of the sensory system expected to result from muscular fatigue can be compensated by the addition of other sensory information for the benefit of the motor control system. However, to

our knowledge, no studies have been performed to determine the ability of the system to take advantage of such supplementary information to improve performance outcomes.

The sex (biology) and/or gender (social expression) of the individual are of additional consideration with respect to the fatigue response. There are well-known differences between men and women in terms of anthropometrics, muscle size, and muscle fiber content (Ditor & Hicks, 2000; Hicks, Kent-Braun, & Ditor, 2001; Hunter, Critchlow, & Enoka, 2004), and recent studies suggest differences in motor compensatory strategies in response to fatigue (Emery & Côté, 2012; Fedorowich, Emery, Gervasi, & Côté, 2013). The size of exercised muscles, and therefore the amount of sensory signaling, has also been proposed to have a role in the determination of exercise tolerance (Rossman, Venturelli, McDaniel, Amann, & Richardson, 2012) and may be relevant to the discussion of sex differences in the fatigue response. In addition, Han et al. (2015) observed an interaction between fatigue and sex, where sensitivity to two-point distinguishability of women was affected by fatigue to a greater degree than that for men. Studies on sex differences in the fatigue response may provide some explanation for the higher prevalence of musculoskeletal injuries of women (Tjepkema, 2003; Vézina, 2011).

The objectives of this study were to assess the sex-specific relationships between motor and sensory adaptations to repetitive arm motion–induced neck/shoulder fatigue, and to measure how providing additional sensory stimulation affects these adaptations. We hypothesized that changes in motor outcomes would develop as sensory acuity diminished with fatigue. Furthermore, we hypothesized that changes to an individual's kinematic patterns (i.e., cycle-to-cycle variability of joint angle) and to his or her sensory system (assessed by means of light-touch detection threshold) would be negatively correlated as fatigue develops (i.e., motor variability would increase as sensory acuity decreased). We also hypothesized that periodically providing sensory stimulation to the main fatiguing muscle would influence the motor response and result in an increased endurance in the fatigue-inducing task. Finally, we hypothesized that men and women would show differences in their fatigue response and would be influenced differently by the sensory intervention.

Methods

Participants

A convenience sample of 25 healthy young adults was recruited through personal contacts and advertisements to participate in this study. All subjects were right-hand dominant. Subjects were excluded if they had a history of neurological, musculoskeletal, or cardiovascular disorders that would affect performance of the experiment or if they had significant exposure to tasks requiring a high endurance of musculature of the neck/shoulder area (e.g., elite athletes). Two participants were excluded because their level of recreational activity and history of injury, which were only recognized following the data collection phase. The final sample was 23 healthy young adults (12 men [age 23 (*SD* 2.5) years, height

169.3 (*SD* 11.0) cm, weight 72.7 (*SD* 8.0) kg] and 11 women [age 23.4 (*SD* 1.5) years, height 160.4 (*SD* 6.3) cm, weight 55.6 (*SD* 8.2) kg]). All subjects completed a Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology, 2002) to ensure that they did not present general health risk factors. The study was performed at the Occupational Biomechanics and Ergonomics Laboratory of the Jewish Rehabilitation Hospital in Laval, Quebec. Prior to commencing the study, all subjects provided informed consent approved by the research ethics board of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal.

Instrumentation

Sensitivity to light touch was determined using a kit of 20 nylon Semmes-Weinstein monofilaments (Touch-Test™ Sensory Evaluator; North Coast Medical Inc., Gilroy, CA). The monofilaments range in thickness from 1.65 to 6.65 on a logarithmic scale that results in applied forces ranging from 0.008 to 300 g (Bell-Krotoski, Fess, Figarola, & Hiltz, 1995). Sensory testing was conducted at three muscle sites: right anterior deltoid (AD), right upper trapezius (UTR), and right bicep brachii (BIC). The AD filament was applied slightly below the muscle belly; the UTR was slightly medial to the muscle belly; and the BIC was slightly above the muscle belly. An area of 1 cm^2 at each site was shaved and washed with alcohol to remove any hair that might interfere with the use of these filaments. The use of Semmes-Weinstein monofilaments for determining sensitivity to light-touch point pressure has been accepted by the Peripheral Neuropathy Association, and the proposed protocol was validated by Berquin, Lijesevic, Blond, and Plaghki (2010).

Five high-resolution cameras, part of the Vicon motion capture system (VICON©; Oxford Metrics Ltd., Oxford, UK), were used to record kinematics during the protocol, operating at a sampling frequency of 100 Hz. Three MX3 cameras (Oxford Metrics Ltd., Oxford, UK) and two F20 cameras (Oxford Metrics Ltd., Oxford, UK) were used in this setup. A series of 30 passive and reflective markers were fixed to the skin using double-sided adhesive tape on anatomical landmarks, in accordance with the upper-body version of the Plug-In-Gait marker set (Oxford Metrics Ltd., Oxford, UK; Lomond & Côté, 2010): left and right sides of the forehead both anteriorly and posteriorly, spinous processes of C7, T6, and T12, left and right transverse processes of T1, T8, and L1 (placed 2.5 cm bilaterally from the spinous process), posterior acromion, spine root and inferior angle of the scapula, S1, left and right postero- and anterosuperior iliac crest, sacrum, sternal notch, left and right acromioclavicular joint, right lateral epicondyle, right medial and lateral wrist, right head of the second metacarpal, and tip of the right index finger.

Session Randomization

This study involved two testing sessions: one with a "stimulus-present" (SP) condition and one with a "stimulus-absent" (SA) condition. The order of these conditions was randomized for all subjects. Each subject's two sessions were held at the same time of day and were separated by a minimum of 48 hr and a maximum of 7 days. Both sessions involved identical protocols with sensory testing prior to and immediately following the fatigue-inducing task. The only difference between

the two sessions was that the SP condition involved the application of the Semmes-Weinstein monofilaments at repeated times during the fatiguing sequence, whereas sensory testing only occurred at the start and end in the SA condition (details below).

Quantitative Sensory Testing

Quantitative sensory testing (QST) measures of the AD, UTR, and BIC were always taken in the following order: Testing at the AD was always assessed first, followed by testing at the UTR and BIC in randomized order. All measures of sensory thresholds were conducted with the subject's eyes closed and in a silent environment (Schreuders, Selles, van Ginneken, Janssen, & Stam, 2008; Voerman, van Egmond, & Crul, 2000). Subjects remained standing and motionless with their dominant arm passively resting supine on a cushioned tabletop, their shoulder abducted 90° and horizontally abducted 45° (resting position). The subject was informed which location was to be tested next and when testing would begin, but was not given any further prompts (Gondring & Shields, 2011). Subjects were instructed to verbally acknowledge when they detected the light-touch stimulus over the specified muscle. Sensory testing over all three sites was conducted at baseline and immediately after the fatigue-inducing sequence.

Each monofilament was applied at an angle of 90° to the surface of the skin until it buckled (Gondring & Shields, 2011; Rommel, Malin, Zenz, & Jänig, 2001; Tracey, Greene, & Doty, 2012). During baseline measures, sensory testing at each site began with the thinnest filament, representing 0.008 g of force, and was increased thereafter in ascending order of thickness. In addition, during the SP condition, sensory thresholds of the AD were assessed during breaks in the fatigue-inducing protocol. For these intermediate measures, testing at the AD always began with a monofilament representing two scores lower than the previously identified threshold. For the purpose of consistency, posttask sensory testing maintained the same procedure of starting with a filament two scores below the baseline measures for each of the three sites. If the monofilament slipped or the subject reported a false positive, the researcher resampled the monofilament in question (Massy-Westropp, 2002).

Fatigue-Inducing Sequence

A repetitive forward–backward pointing task (RPT), performed with the arm maintained at shoulder height, was used to fatigue muscles of the neck/shoulder region. A repetitive pointing apparatus was set up according to each individual's specific anthropometrics. Two cylindrical touch-sensitive targets were adjusted to 100 and 30% of the subject's reach at shoulder height and along the midline of his or her body (Figure 1). With the subject's shoulder flexed 90°, an elliptically shaped mesh barrier (major axis: 24.5 cm; minor axis: 20.5 cm) was placed below the functional range of motion of the elbow joint. Participants were instructed to move the index finger of the dominant arm between the targets, at a rate of 1 Hz. Each target was touch sensitive, producing both a visual and an auditory response to their touch. A metronome was provided to help the subject to maintain a pace of 1 Hz. Participants were instructed to continue the procedure as long as possible,

Figure 1 — Experimental setup of a subject standing at the repetitive pointing apparatus.

until we stopped them. This experimental task has been used in several experiments to fatigue the neck/shoulder because of the requirement to both maintain the arm at shoulder height and repetitively move it forward and backward. This functional task has shown increases through time in heart rate and neck/shoulder muscle activity amplitude recorded during the task, and has shown decreases in maximal voluntary force of the corresponding neck/shoulder muscles immediately after the task compared with before, all consistent with what we know of the effects of fatigue on the motor system (Fuller et al., 2009).

The fatigue-inducing sequence was structured around repeated blocks of 2.5 min. Each block consisted of one repetitive pointing phase and one resting phase. The repetitive pointing phase consisted of 2 min of performing the RPT. Subjects were prompted to report their self-perceived neck/shoulder exertion following each minute of the RPT using the Borg CR10 scale (Borg, 1982;

Cantu et al., 2014; Fedorowich et al., 2013; Fuller et al., 2009). A Borg rating of 0 referred to a rating of perceived exertion of "nothing at all," a rating of 7 corresponded to "very strong," and a rating of 10 referred to the experience of "very, very strong (maximal)" perceived exertion.

The resting phase consisted of 30 s of rest with the subject standing and his or her right arm supported on a table such that the elbow was straight and the shoulder abducted 90° and horizontally abducted 45° (same posture as baseline sensory testing). The subject remained as still as possible with her or his eyes closed during this time. The SA condition involved silent uninterrupted standing in this position, whereas the SP condition involved sensory testing at the AD muscle using monofilaments followed by the application of five more stimuli using a monofilament of size 5.07 (equivalent to 0.1 N) at a rate of one stimulus per second just prior to the start of the ensuing repetitive pointing phase.

Blocks of alternating repetitive pointing and resting phases were repeated until the subject met any of the following stoppage criteria (whichever occurred the earliest): The subject reported a score of 8 or greater (i.e., greater than "very strong") on the modified Borg CR10 scale at any point during that block, could not maintain 90° shoulder flexion during the RPT, or could not maintain the 1-Hz pointing pace (Cantu et al., 2014; Fedorowich et al., 2013; Fuller et al., 2009). Individuals who did not report a score of 8 within 45 min of performing the task were allowed to stop. Immediately following completion of the fatigue-inducing procedure, the subject was instructed to return to resting position where sensory testing was conducted over all three muscles sites, in the same order as for the baseline measures.

Data Analysis

Sensory threshold measures were initially recorded in terms of their marked value. These values were converted to their gram equivalent value based on the table presented in the associated Touch Test™ Sensory Evaluator operation manual, which were validated during the pretest pilot phase. Kinematic data were collected during the middle 30 s of each minute of the repetitive pointing phase. The first 30-s block recorded was retained as the data for the baseline, starting (Start) condition, and the final 30-s block recorded was labeled "End." Forward and backward pointing movements were partitioned as a function of the target activation signal. Only the forward movements were considered for analysis.

Marker trajectories were low-pass filtered using a digital second-order Butterworth filter with a cutoff frequency of 7 Hz and zero-phase lag. Elbow flexion–extension and shoulder horizontal abduction–adduction angles were computed using MATLAB software (The MathWorks, Waltham, MA). Elbow flexion–extension angle was calculated based on markers of the right shoulder, right elbow, and midpoint between the two wrist markers. Shoulder horizontal abduction–adduction was defined as the angle between markers of the left shoulder, right shoulder, and right elbow in the transverse plane. A maximum of 15 forward movements could be identified from each 30 s of recording because the rhythm of the task for both forward and backward pointing movements was 1 Hz. In some cases, fewer movements were seen—for instance, when participants occasionally missed the touch targets. All identified forward movements were first

normalized to 100% of their forward movement cycle duration and expressed in terms of equidistant samples representing 10% of the movement cycle. Shoulder and elbow mean angles and cycle-to-cycle standard deviations were computed across all forward movements at each 10% of the movement cycle. An overall mean angle was calculated to represent the average joint angle within each block of recording. Furthermore, a single coefficient of variation (CV) representing the cycle-to-cycle variability of joint angles was calculated by normalizing the pooled standard deviations of angular measures across different time points to the overall mean angle (Srinivasan, Rudolfsson, & Mathiassen, 2015).

Shoulder–elbow coordination was defined by calculations of the continuous relative phase (Hamill, van Emmerik, Heiderscheit, & Li, 1999). In a procedure identical to that for shoulder and elbow angle and CV calculations, time curves for continuous relative phase were normalized to 100% of each forward movement's duration and were sampled at each 10% of the movement cycle (Srinivasan et al., 2015). An overall mean relative phase angle was computed to represent all forward movements for each 30-s block. Pooled standard deviations of continuous relative phase measures were normalized to the mean relative phase angle to calculate a CV representing the cycle-to-cycle variability of the shoulder–elbow coordination of that block.

Statistical Analysis

Normality of data was assessed using the Shapiro–Wilk test of normality. For normally distributed data, a Condition × Sex repeated-measures analysis of variance (ANOVA) was run on measures of time to task failure, and a Time (Start and End) × Condition (SA and SP) × Sex (men and women) repeated-measures ANOVA was run on mean shoulder, elbow, and shoulder–elbow coordination angles. Because data for CV and sensory thresholds were not normally distributed, nonparametric Friedman ANOVAs of Time × Condition were run on CV of shoulder, elbow, and shoulder–elbow coordination angles and sensory thresholds at each site. The Friedman ANOVAs were conducted for the entire sampled population, as well as for each sex independently. Post hoc Wilcoxon paired comparisons were run to establish where significant differences existed. Indices of effect size were calculated by averaging each subject's End–Start change expressed as a percentage of the starting, baseline value. Finally, Spearman correlation coefficients were computed for the End–Start change in QST measures versus End–Start change in CV. Correlations were performed for the entire sampled population, as well as separately for men and women. Significance was set as $p < .05$ for all analyses, and all analyses were conducted using SPSS statistical software (IBM SPSS Statistics, Armonk, NY).

Results

Effects of the RPT

Subjects performed the pointing task before being terminated because of scoring 8/10 for an average of 19.7 (*SD* 13.6) min. No differences in time to termination

were observed as a function of condition, $F(1, 21) = .04$, $p = .87$, and/or sex, $F(1, 21) = 1.45$, $p = .24$. Of the 46 data collection sessions, all but eight sessions involved the participants expressing a rating of perceived exertion of 8 or higher within 30 min of repetitive pointing. Three men completed the full 45-min pointing task in both of their sessions, one man completed 45 min of the pointing task in the SA condition (but only 17 min of the task in the SP condition), and one woman completed 45 min of the pointing task in the SP condition (but only 24.5 min of the task in the SA condition). Thus, removing the eight sessions where subjects did not report a Borg rating of perceived exertion of 8 or higher led to an average time for task performance of 14.4 (*SD* 7.9) min. Data from the eight "non fatiguing" sessions were included in all of the subsequent analyses because none of these datasets contained any clear outliers in their outcome measures.

Effects of RPT on Motor Patterns

Measures of shoulder, elbow, and shoulder–elbow coordination mean angles were shown to be normally distributed according to the Shapiro–Wilk test of normality. Statistical analysis revealed significant Time effects for shoulder mean angle, $F(1, 21 = 9.49$, $p = .006$, and mean relative phase angle, $F(1, 21) = 9.63$, $p = .005$. Shoulder mean angle increased over time while mean relative phase angle decreased over time. No significant effects were observed for measures of mean elbow angle (Figure 2a–2c).

CV for shoulder, elbow, and shoulder–elbow coordination angles failed to meet the assumption of normality. Therefore, nonparametric Friedman tests were
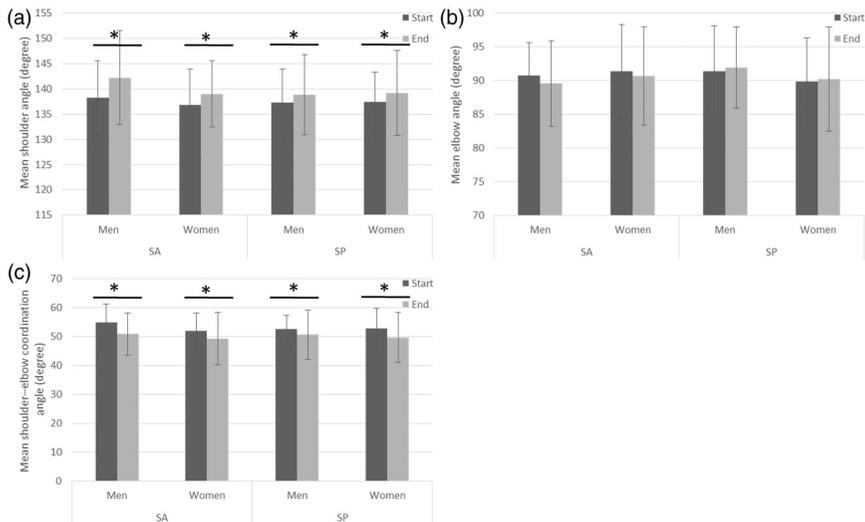

Figure 2 — Effects of fatigue on (a) mean shoulder angle, (b) mean elbow angle, and (c) mean shoulder–elbow coordination angle displayed for men and women in the SA and SP conditions. SA = stimulus absent; SP = stimulus present. *Time effect, $p < .05$.
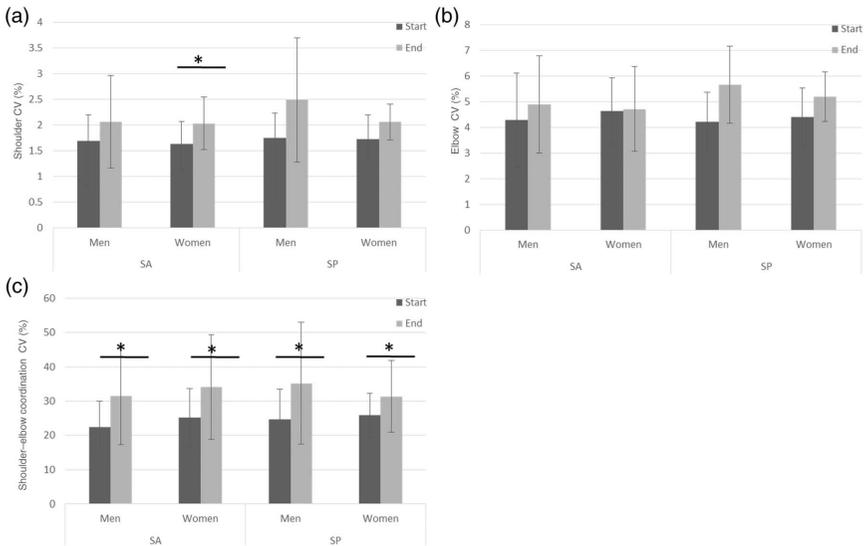
Figure 3 — Effects of fatigue on (a) CV of shoulder angle, (b) CV of elbow angle, and (c) CV of shoulder–elbow coordination angle displayed for men and women in the SA and SP conditions. CV = coefficient of variation; SA = stimulus absent; SP = stimulus present. *Time effect, $p < .05$.

applied to these data. When assessed across the entire sampled population, Friedman ANOVA rendered significant chi-square values for each variable: shoulder CV ($\chi^2 = 13.70$, $p = .003$), elbow CV ($\chi^2 = 9.10$, $p = .028$), and shoulder–elbow coordination CV ($\chi^2 = 28.62$, $p < .001$). Post hoc Wilcoxon pairwise comparisons identified significant increases from Start to End for shoulder CV in both SA ($Z = -3.16$, $p = .002$) and SP ($Z = -2.83$, $p = .005$) conditions (where the average change in CV represents 23.5% and 33.3% of each individual's starting values, respectively), in measures of elbow CV in the SP condition ($Z = -3.10$, $p = .002$; where the average change in CV represents 31.6% of each individual's starting values), and in measures of shoulder–elbow coordination CV in both SA ($Z = -3.68$, $p < .001$) and SP ($Z = -3.68$, $p < .001$) conditions (where the average change in CV represents 38.0% and 30.6% of each individual's starting values, respectively; Figure 3a–3c).

When men and women were assessed independently, the Friedman ANOVA rendered significant chi-square values for shoulder CV for women ($\chi^2 = 10.31$, $p = .016$) and for CV of shoulder–elbow coordination angle for both men ($\chi^2 = 18.00$, $p < .001$) and women ($\chi^2 = 11.40$, $p = .010$). Post hoc Wilcoxon comparisons identified significant increases across time for shoulder CV for women in the SA condition ($Z = -2.13$, $p = .033$) and for coordination angle CV for both men and women in both SA (men: $Z = -2.43$, $p = .015$; women: $Z = -2.76$, $p = .006$) and SP (men: $Z = -2.90$, $p = .004$; women: $Z = -2.22$, $p = .026$) conditions.

Effects of RPT on QST

Measures of quantitative sensory thresholds failed to meet the assumption of normality. When assessed across the entire sampled population, the Friedman ANOVA of QST at the AD rendered a chi-square value of 25.08, which was significant ($p < .001$). Post hoc Wilcoxon pairwise comparison identified significant differences between Start and End measures at the AD in the SP condition ($Z = -3.92$, $p < .001$), where the average change in sensory thresholds at the AD represents 1093% of each individual's starting value, and between End-task measures in the SP and SA conditions ($Z = -3.74$, $p < .001$). Assessed independently for men and women, the Friedman ANOVA of QST at the AD rendered a chi-square value of 12.20 ($p = .007$) for men and 15.40 ($p = .002$) for women. Values increased significantly from 0.15 (SD 0.20) to 0.62 (SD 0.59) g for men in the SP condition ($Z = -2.71$, $p = .007$) and from 0.14 (SD 0.14) to 0.98 (SD 1.10) g for women in SP condition ($Z = -2.85$, $p = .004$). The Friedman ANOVA did not reveal significance at any of the two other sites when assessed for the sampled population as a whole, or for either sex considered independently. Significant comparisons of QST measures at each site as a function of condition and sex are summarized in Figure 4a–4c.
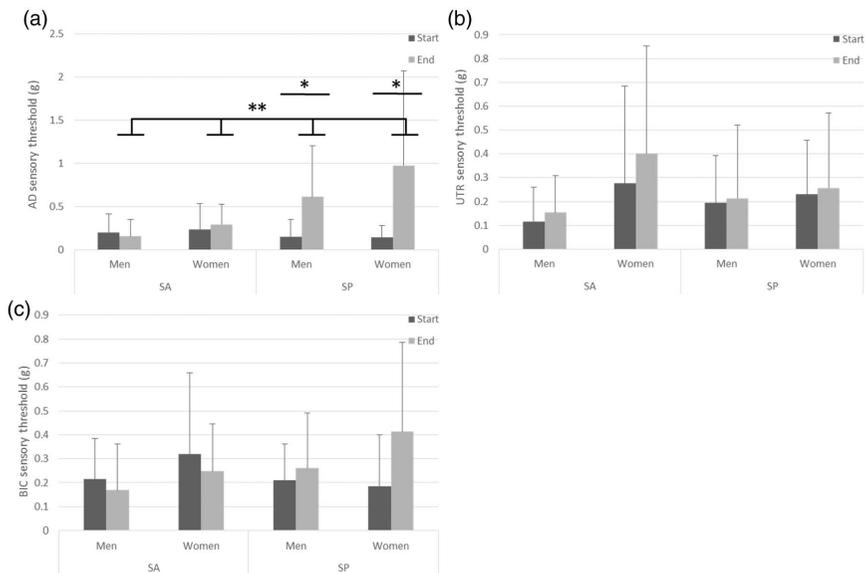

Figure 4 — Effects of fatigue on (a) QST at the AD, (b) QST at the UTR, and (c) QST at the BIC displayed for men and women in the SA and SP conditions. QST = quantitative sensory testing; AD = anterior deltoid; UTR = upper trapezius; BIC = bicep brachii; SA = stimulus absent; SP = stimulus present. *Time effect, $p < .05$. **Condition effect, $p < .001$.

Correlation Between Sensory and Motor Changes

Correlations between the changes from Start to End in measures of QST and variability of arm kinematics (as assessed through CV of shoulder, elbow, and shoulder–elbow movements) revealed no significant relationships when the sampled population was assessed as a whole. When stratified as a function of sex, three significant relationships emerged: two for men and one for women. A significant positive correlation was found between fatigue-related changes in UTR-QST and changes in CV of shoulder–elbow coordination phase angle for men in the SA condition ($r = .65$, $p = .021$; Figure 5a). In other words, in the SA condition, subjects (men only) with the greatest increase in sensory threshold at the UTR were the ones who displayed the greatest increase in variability of shoulder–elbow coordination angle with fatigue. A significant negative correlation was found between changes in UTR-QST and changes in shoulder CV for men in the SP condition ($r = -.60$, $p = .038$; Figure 5b). In other words, in the SP condition, subjects (men only) with the greatest increase in sensory threshold at the UTR were the ones who displayed the smallest increase in shoulder angle variability with fatigue. A significant positive correlation was found between change in AD-QST and change in shoulder CV for women in the SP condition ($r = .76$, $p = .007$; Figure 5c). In other words, in the SP condition, subjects (women only) with the greatest increase in sensory threshold at the AD were the ones who displayed the largest increase in shoulder angle variability with fatigue.
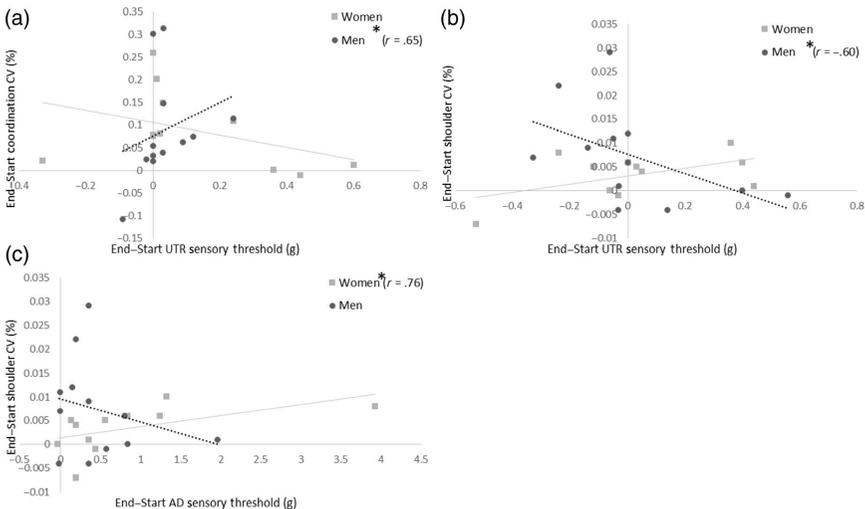

Figure 5 — Correlations between the Start and End differences in (a) UTR-QST and shoulder–elbow coordination CV in the SA condition, (b) UTR-QST and shoulder CV in the SP condition, and (c) AD-QST and shoulder CV in the SP condition. *Note.* Solid line shows trend of data in women; dotted line shows the corresponding trend for men. UTR = upper trapezius; QST = quantitative sensory testing; CV = coefficient of variation; SA = stimulus absent; SP = stimulus present; AD = anterior deltoid. *$p < .05$.

Discussion

Motor and Sensory Adaptations to Fatigue-Inducing Pointing Task

Our results show that motor characteristics are influenced by a light-load, repetitive-motion fatigue-inducing task. Mean shoulder horizontal abduction–adduction angles were significantly greater in the final minute of the task (End) than in the first minute (Start), whereas mean shoulder–elbow relative phase was significantly decreased as a function of time. These results are consistent with results from previous studies that used repetitive upper-limb tasks and that demonstrated shifts in posture and compensatory changes in coordination, interpreted as strategies to decrease the load on fatiguing muscles (Côté et al., 2002, 2005; Cowley et al., 2014; Forestier & Nougier, 1998; Gates & Dingwell, 2011). However, this is the first time that upper-limb coordination changes have been quantified using the continuous relative phase approach.

In addition, CV of shoulder and elbow joint angles and that of shoulder-elbow coordination angles increased as a function of time. Increased cycle-to-cycle variability with fatigue has been found in previous studies and may either be attributed to a lessened ability to produce accurate movements (Huysmans et al., 2008; Missenard et al., 2008) or be representative of a motor strategy implemented by the individual to maintain overall performance despite showing signs of muscular fatigue (Fedorowich et al., 2013; Fuller, Fung, & Côté, 2011). In line with the latter perspective, our results support the interpretation that adaptations to fatigue are task specific whereby differences between experimental protocols may be the reason for minor differences between study results (i.e., relating to amount and region of motor adaptations).

Analysis of measures of quantitative sensory thresholds revealed significant time-dependent increases in light-touch detection thresholds at the AD in the condition where sensory stimulation was provided (for both men and women). In addition, fatigue-terminal AD thresholds were significantly greater in the condition with sensory stimulation than when stimulation was absent (Time × Condition interaction). Despite previous research demonstrating that sensory supplementation has a beneficial effect on sensory function (Freyer, Reinacher, Nolte, Dinse, & Ritter, 2012; Kalisch, Tegenthoff, & Dinse, 2008), our data suggest that stimulation may add the effects of fatigue on the sensory system and lead to a larger decrease in sensory detection capability. Results from other experimental fatigue protocols have found significant increases in sensory thresholds of both fatigued and nonfatigued muscles (Han et al., 2015; Kosek & Lundberg, 2003; Moufflet & Côté, 2015). In our study, significant effects of fatigue were only observed in the SP condition and at a single muscle. Differences between our results and those of previous studies (Han et al., 2015; Kosek & Lundberg, 2003; Moufflet & Côté, "Identification of objective measures of neck/shoulder fatigue during simulated auto work at shoulder height," in preparation) may be attributed to differences between experimental protocols, with our protocol involving fatigue induced by multijoint movements rather than under isometric conditions; differences in the mechanical roles of the selected muscles, with the AD having a primary mover

role in task performance and the UTR having a shoulder stabilizing role; or effects of the mode of sensory threshold tested (i.e., light-touch detection, two-point distinguishability, and point-pressure threshold).

Association Between Motor and Sensory Changes

When all subjects were grouped together, we observed no significant correlations between sensory and motor changes with fatigue, contrary to our initial hypothesis. This may be explained by men and women presenting trends in opposite directions. When separated in sex subgroups, significant correlations between fatigue-related changes in sensory threshold (which were themselves significant) and measures of motor variability (which were themselves significant) were only found for women in the SP condition. In other words, women with the greatest increase in sensory threshold at the AD were the ones who displayed the greatest increase in shoulder variability. For men, significant correlations were found between fatigue-related changes in sensory thresholds of the UTR (which were themselves not significant) and measures of motor variability (which were themselves significant). In other words, men demonstrated both a significant positive correlation between changes in UTR-QST and CV of shoulder-elbow coordination angles in SA and a negative correlation between changes in UTR-QST and CV of shoulder angles in SP. These correlations lend further support to the notion that motor and sensory responses to fatigue have a complex interaction, especially in the context of sex differences. Differences in sensorimotor correlations between men and women support previously observed sex differences in how fatigue induced by the same task affects men and women differently (Fedorowich et al., 2013), where different muscles get more fatigued or show compensatory effects in men compared with women. In turn, this may explain sex differences in susceptibility to musculoskeletal disorders in different muscles. To our knowledge, no previous research has been conducted correlating fatigue-induced changes in sensory threshold and motor patterns. This novelty is emphasized by the fact that we studied not only kinematic patterns of individual joints but also interjoint coordination patterns, reinforcing the notion of a sensorimotor link that spans complex, multijoint control.

Our interpretations of these correlations are in line with the proposed theories of the sensorimotor system and its role in motor planning. Studies of fatigue and/or sensory reweighting have proposed that altered afferent signaling contributes to the perception of effort (Luu, Day, Cole, & Fitzpatrick, 2011) and contributes to associated altered motor patterns (Carpenter, Murnaghan, & Inglis, 2010; Eva-Maj, Hans, Per-Anders, & Mikael, 2013). The results of our study are consistent in showing that disturbances of the sensory system, quantified by increases in sensory thresholds (i.e., declines in afferent signaling of event detection), are related to, and possibly part of, mechanisms influential in generating greater changes in motor patterns.

If motor variability changes and motor variability and sensory thresholds are related, an alternative is needed for the lack of significant change in sensory thresholds in the SA condition. Increased motor variability has been proposed to prolong performance and decrease risk of injury (Côté, 2014; Madeleine, 2010; Srinivasan & Mathiassen, 2012) and may therefore present similar

benefits of decreasing the effects of the RPT on QST. This relationship lends support to the observation of significant correlations between UTR-QST and measures of motor variability despite UTR-QST itself not being significantly increased as a result of fatigue. Alternatively, this could be explained by the fact that we did not record QST at all muscles that could have contributed to the multijoint task and the associated changes in CV, which may also present an explanation for the discrepancies between the QST results of our study involving multijoint repetitive motion and similar studies involving isometric contractions where the benefits of increasing motor variability are not possible.

In summary, the results of this study are in line with our initial hypothesis in such a way that increases in sensory thresholds can be related to increases in variability in the motor system and that these relationships may be different for men and for women. However, our hypothesis did not consider how the rise in one mode may influence the other. Further research is needed to understand how fatigue-related changes to sensory thresholds and motor variability are related in real time, where transient changes in one may be quickly compensated by changes in the other set of variables.

Influence of Sensory Supplementation on Fatigue-Associated Changes

Sensory supplementation was provided in the form of five point-pressure stimuli of 0.1 N applied at a rate of 1 Hz above the AD. A stimulus magnitude of 0.1 N was selected based on previous studies noting that 1 N of contact force was sufficient to influence motor patterns (Franzén et al., 2011; Kimura et al., 2012; Vuillerme & Nougier, 2003) and that 0.1 N would be at least four times greater than any individual's sensory thresholds in both nonfatigued and fatigue-terminal states. Stimulus was applied to the AD because this was perceived as the main agonist in our protocol.

Our initial hypothesis was that providing supplementary sensory information to a fatiguing muscle would compensate for the loss in sensitivity presumably produced by this fatigue, and that, in turn, this would influence the development of motor compensatory strategies and result in increased time to task termination compared with no sensory supplementation. However, according to our results, providing supplemental sensory information did not appear to affect an individual's endurance. It is possible that the light-touch stimuli were not strong enough to represent a significant impact on the fatigue response or that participants made no use of this supplementation in terms of altering overall task performance. This latter interpretation is in line with our previous studies where additional perturbations applied on the system as fatigue developed (postural perturbations: Fuller et al., 2013; additional weight: Cantu et al., 2014) had no additional effect on the time to task termination, which was interpreted to reflect the ability of the system to use alternative fatigue-compensatory strategies. Alternatively, given that previous research has presented evidence of sensory reweighting in the context of muscular fatigue (Billot, Handrigan, Simoneau, Corbeil, & Teasdale, 2013; Hlavackova & Vuillerme, 2012; Pradels, Pradon, Hlavačková, Diot, & Vuillerme, 2013; Vuillerme et al., 2005), it is possible that the effects of sensory stimulation could have been more beneficial toward motor performance if applied to an area of

sensory upregulation rather than at the site of the AD that had the greatest likelihood of developing fatigue.

Although there were no differences in time to task termination, time effects on the sensory thresholds at the AD in the SP condition only, as well as the different correlations between men and women in either condition, support the role of sensory signaling in determining the fatigue response and the influence of supplementation on sensorimotor characteristics on the way to fatigue. Increases in sensory thresholds at the AD may be evidence of changes in the fatigue-related sensory reweighting process, or they may be evidence of increased muscular fatigue at the AD following an alternatively developed motor response to fatigue. Providing sensory information has been shown to alter mechanisms of sensory reweighting (Billot et al., 2013; Hlavackova & Vuillerme, 2012; Pradels et al., 2013; Vuillerme et al., 2005) as well as exert an influence on postural control (Franzén et al., 2011) and variability in motor unit discharge (Kouzaki, Kimura, Yoshitake, Hayashi, & Moritani, 2012). The positive relationship between AD-QST and shoulder CV for women presents further support for sex differences in the fatigue response, where women may be better able to integrate sensory information from the muscles into their motor planning, or may be more reliant on doing so, when compared with men. An electromyographical analysis of how muscular activity of the AD changes as a function of conditions, and how the amplitude of muscle activity correlates with changes in sensory thresholds, would lend strong support for this notion.

Limitations

The results of this study are limited to assessing the effects of repetitive motion–induced fatigue on the neck/shoulder complex in a healthy young adult population. In addition, the short transient resting phases during the fatigue-inducing sequence may have allowed individuals to slightly recover from fatigue at different rates, thus influencing their overall performance in ways that could vary from one participant to another. The design of this protocol implied a work:break ratio of 4:1, consistent with other methods used in our laboratory (Moufflet & Côté, in preparation). The length of the resting phase was a trade-off between having more time to test QST and giving too much recovery time to the participant. The stopping criteria, based on a rating of perceived exertion, were consistent with studies of similar protocols that have demonstrated significant increases in muscle activity across the musculature of the neck/shoulder complex, including AD, BIC, and UTR (Cantu et al., 2014; Fedorowich et al., 2013; Fuller et al., 2009; Emery & Côté 2012). The use of the Borg CR10-based criteria to identify fatigue in itself implies some variability in the physiological fatigue state across participants. The stopping criterion of 45 min of task performance was selected to correspond to when individuals would take breaks in a working environment. All of these methodological choices likely influenced our observation of a range of times to task termination, and even the occurrence where some participants never reached the Borg CR10 rating of 8 by 45 min. We believe that the observations of significant effects despite this variability in time and state of physiological fatigue lend strength to these observations that hold despite these sources of variance, although this makes it difficult to identify the exact sources of

these effects. Further studies are needed to help identify the mechanisms under-lying several of our findings.

Conclusion

The results of this study support the conclusion that a repetitive-motion fatigue-inducing task leads to motor adjustments to sustain the task. During the SA condition, individuals altered their pointing movements but showed no change in sensory acuity. Presenting additional sensory information (light touch) at the site of a fatiguing muscle is proposed to influence the accuracy of the sensory system and the relationship between motor and sensory adaptations to muscular fatigue. However, the effects of sensory stimulation appear to remain very much at the local, sensory level. In addition, the influence of sensory supplementation on coordination between motor and sensory changes seemed to differ between men and women, giving support to sex-specific profiles of the fatigue response (which could in turn have an impact on sex differences in injury risk). The absence of an effect of sensory supplementation on time to task termination seems to contrain-dicate such an intervention in clinical or ergonomic settings, although differential effects on different muscles between sexes may support the use of sensory supplementation depending on the task, sex, and anatomical locations of vulner-abilities, weakness, or symptoms. Further studies are needed to fully understand the potential of such an intervention on occupational health.

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