The Effect of Muscle Fatigue on Position Sense in an Upper Limb Multi-joint Task

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The purpose of this study was to estimate the extent to which muscle fatigue can impact on the position sense in the upper limb. Twelve healthy volunteers were asked to do a reaching task while grasping a wooden block and match the block’s position with a corresponding target displayed on a flat screen, without vision. Following that, subjects performed resistive exercises with Thera-band strips until fatigue was induced and then the position sense task was repeated. A significant change in the endpoint position was observed after fatigue, in the up/down direction ($p \leq .001$). The variability of endpoint positions in up/down direction was also significantly increased after fatigue ($p \leq .03$). There was no significant change in endpoint orientation but there was a significant fatigue × orientation effect on endpoint rotational variability. In a follow-up experiment, a group of subjects repeated the same protocol, but with a period of quiet rest between the two position sense tasks. In that group, there were no differences in endpoint position, orientation or variability. Muscle fatigue is an important factor that should be taken into consideration during the treatment of musculoskeletal injuries as well as athletic training.

Keywords: electromyography, neuromuscular control, position sense, reaching task, shoulder joint

The glenohumeral joint is the most mobile joint in the human body, and is inherently unstable (Williams & Warwick, 1986). However, static (ligament and capsule) and dynamic (muscle) stabilizers around this joint can compensate for the lack of stability (Wilk et al., 1997). For stability to be achieved, muscles around the joint should function in a coordinated manner. This is fully dependent on the commands sent from spinal and higher levels of the nervous system (Wilk & Arrigo, 1993). Proprioception was originally defined by Sherrington (1906) as the afferent information arising from mechanoreceptors located in the muscles, tendons, ligaments and skin around the joint. Among these, muscle spindles are considered as important proprioceptive receptors found in skeletal muscles (Baldissera et al.,
The output of muscle spindles can be altered by the increased intramuscular concentration of several contractile substances (Djupsjobacka et al., 1994; Djupsjobacka et al., 1995a; Djupsjobacka et al., 1995b). In addition, the sensitivity of muscle spindles is controlled by gamma motor neuron system. Therefore, factors which reduce gamma motor neuron excitability can also reduce muscle spindle’s sensitivity, resulting in impairment of proprioception (Hurley, 2002). The afferent (proprioceptive) signals from peripheral receptors are sent to the central nervous system (CNS) where they are integrated with other sensory modalities, as a basis for an appropriate motor response (Myers & Lephart, 2000). Several studies emphasize the important role of proprioception in the control of limb posture (Rothwell et al., 1982; Sanes et al., 1985) and in the specification of movement direction (Ghez et al., 1990). Cordo et al. (1990, 1993, 1994) also showed in a series of experiments that the CNS uses the information related to both angular position and velocity from proprioceptive input to coordinate movement sequence. Therefore an optimal and coordinated joint movement and stability is highly dependent on the afferent (proprioceptive) signals from mechanoreceptors.

The relationship between proprioception and stability has been demonstrated in several studies. Smith & Brunolli (1989) compared proprioception in dislocated shoulders with uninjured ones and reported that proprioception was significantly decreased in dislocated shoulders. This might be due to a partial deafferentation that occurs after an injury to the joint (Lephart & Jari, 2002). In another experiment, athletes with chronic anterior shoulder instability were shown to have a significant deficit in their proprioception (Lephart et al., 1994). On the other hand, Lephart and Henry (1996) suggested that proprioception deficits themselves (caused by injury or not) can also produce instability in a joint. So whether proprioception deficits are the cause of, or the result of joint instability, the association between these two has been well demonstrated by investigators. When the shoulder joint becomes unstable, it is prone to muscular and ligamentous injuries. In two longitudinal studies, Robinson et al. (2002, 2006) showed that 55.7% of patients with shoulder instability are likely to develop injuries in their joint within two years of the primary instability. Lephart and Henry (1996) suggested that people with functional instability who also suffer from a deficit in proprioception are more likely to develop subsequent injuries.

Muscle fatigue has been suggested as one of the factors that may be associated with proprioception deficit, joint instability and injury (Lephart & Jari, 2002). In everyday life, muscle fatigue is a subjective sensation such as increased effort of maintaining force, or a discomfort and pain associated with muscular activity (Oberg et al., 1994). Enoka and Stuart (1992) define fatigue as impairment in performance that leads to both the inability to maintain a certain level of force and an increased perception of task difficulty. The origin of fatigue might be central, peripheral or both. Fatigue of the CNS (central) includes neurobiological mechanisms of change in subjective effort, motivation, mood and pain tolerance as well as the mechanisms that inhibit motor drive in upper regions of the brain (Gandevia, 1998). Peripheral muscle fatigue is the inability of the muscle fibers to sustain a given intensity (Brooks et al., 2000). A 10-year study of hamstring muscle injuries in intercollegiate football players reported “an obvious association” between these injuries and muscle fatigue (Heiser et al., 1984). Pinto et al. (1999) and Gabbett (2000) also reported that in athletes, the frequency of injury increased as the game progressed, with a higher
Muscle Fatigue and Position Sense

likelihood of injury observed during the last period of games compared with the first, suggesting the role of muscular fatigue or accumulative micro traumas in the injury mechanism. Finally, Smith and Brunolli (1989) reported that the injury rate and fatigue scores decrease as the players become better conditioned and thus more fatigue-resistant. Based on these studies, fatigue can be considered as an important factor in the development of injuries. The exact mechanism under which muscular fatigue can increase the chance of injury is not well known yet; however, Tripp et al. (2004) suggest that muscular fatigue can cause a deficit in proprioceptive mechanisms and eventually instability in the joint, which itself is a predisposing factor for injury. Voight et al. (1996) suggest that the deficit in proprioception happens when the mechanoreceptors in the muscles around the shoulder become inefficient and dysfunctional following fatigue.

Several authors have investigated the effect of muscle fatigue on proprioception of the shoulder. According to Matthews (1982), Sherrington described 4 submodalities of “muscle sense” in Schafer’s Textbook of Physiology: (1) posture, (2) passive movement, (3) active movement, and (4) resistance to movement. These submodality sensations correspond to the contemporary terms joint position sense (posture of segment), kinesthesia (active and passive), and the sense of resistance or heaviness. Among these components, position sense has received the greatest attention, in the context of fatigue. Voight et al. (1996) measured the shoulder repositioning ability of subjects with an isokinetic dynamometer. They reported a significant increase in the position sense error after muscular fatigue. Other studies investigating shoulder fatigue also reported similar findings (Carpenter et al., 1998; Myers et al., 1999). In addition, similar experiments on the elbow also showed an alteration in position sense after both eccentric (Walsh et al., 2004) and concentric exercises (Allen & Proske, 2006) leading to muscle fatigue. In such single joint experiments, the upper limb was usually strapped and fixed to the measurement device and only one joint was free to move. Such strapping and fixation is believed to affect the proprioceptive signals by providing additional sensory feedback (Tripp et al., 2004). To avoid these confounding factors, Tripp et al. (2004, 2007) investigated the effect of fatigue on position sense acuity in an unsupported, functional multijoint task, where they tested the acuity of baseball pitchers in reproducing two arm positions (arm-cocked and ball-release). The result showed a significant difference in the position sense of the upper extremity after fatigue.

To date only a few experiments have investigated the effects of fatigue on position sense in a functional multijoint task. Specifically proprioceptive characteristics associated with the reaching task, a common daily activity, have not been studied in the context of fatigue. Accordingly, the purpose of this study was to quantify the extent to which muscular fatigue alters the position sense of the upper extremity in healthy adult subjects performing reaching. This experiment included a multijoint task, which was accomplished freely without any fixation, similar to an everyday occupational movement. In such a free movement, other joints in the upper limb as well as the trunk might contribute to the task and compensate for the compromised acuity after fatigue. However, we hypothesized that despite the possible movement compensations, muscle fatigue would significantly affect the ability of subjects to reproduce an arm position which would indicate a disruption in the overall arm position sense.
Methods

Subjects

Twelve healthy, right-handed subjects (five females, seven males) with a mean age of 26 years (±3.1) were recruited for the experiment. No subject reported any history of musculoskeletal disease in the upper extremity or in the cervical spine. In addition, none of the subjects was pursuing a professional activity involving extensive physical training of the arm or shoulder (e.g., sport, dancing, music). After the investigators explained the experimental procedure, all subjects provided their informed consent using forms approved by the ethics committee of Center for Interdisciplinary Research in Rehabilitation (CRIR). Subjects could withdraw at any time during the experiment.

Experimental Protocol

The experimental protocol consisted of three phases. At first, subjects performed a position sense measurement task. This was followed by a series of intensive fatiguing exercises, and finally the position sense measurement task was repeated. Together the three phases of the experiment lasted approximately 25 min.

Position Sense Task

We inferred the position sense of the upper limb by asking the subjects to reproduce an arm endpoint position and orientation by reaching to a target in the standing position. Subjects grasped the handle of a light wooden block (15 × 3 × 1.5 cm) between the thumb and index finger (key grip) and stood in front of a computer screen (Figure 1A). The center of the screen was adjusted at the subject’s shoulder level, and set at a distance corresponding to 90% of their arm length (measured from the acromion process to the tip of the middle finger). Subjects’ foot placements were marked on the ground. At the start of a trial, a rectangular target (15 × 3 cm) appeared on the screen in one of three different orientations (vertical or ±35°) (Figure 1B). After a fixed (3 s) delay, vision was blocked by means of Liquid Crystal Display (LCD) glasses. Two seconds later, at the sound of a beep, subjects had to reach forward and place the block on the target, while matching its remembered location and orientation. Finally, subjects had to maintain their final arm position until they heard another beep, signaling the end of the trial (approx. 2.5 s after they had completed their movement); they then had to bring back their arm alongside their body. Vision was restored and the next trial was initiated. Thus, subjects never saw their arm, hand or the target during movement and nor did they receive visual feedback about their performance. Target orientations were presented in a random order (10 trials/condition, for a total of 30 trials). The timing of target presentation as well as motion capture data recording were done using custom software developed in Matlab (The Mathworks, R2007b, Natick, Massachusetts, USA). During testing, subjects were instructed to match the block with the target and do not let it move by pushing it on the Plexiglas. This way, there was no drift in the endpoint after the task. The timing of motion capture data recording was preset and was the same for all subjects. Since the movement speed of all subjects
Muscle Fatigue and Position Sense

was not the same, we extended the recording time for 2.5 s, just to be sure that all subjects had completed the task.

Precautions were taken to avoid other sources of proprioceptive or tactile feedback. First, the screen was placed behind a large Plexiglas plate to provide a uniformly vertical surface. In addition, by selecting a 90% reach distance, the feedback (joint receptor signals as well as the osseous block at the end of the movement) that a fully extended elbow could provide was avoided (Figure 1A).

![Figure 1 — Experimental setup. In A) a subject reaches to the target, while vision is blocked by LCD glasses. Panel B) displays the three different target orientations.](image)

**Muscle Fatiguing Exercise**

The independent variable in this study was muscular fatigue. Since the reaching movement involved multiple joints, several muscles in the arm including both prime movers and stabilizers were active during the task. Thus, a comprehensive protocol was developed, to fatigue most muscles acting as agonists in the experimental task. The fatiguing exercises consisted in a series of resistive arm movements using an elastic band (Thera-Band, blue color, medium resistance, Akron, Ohio, USA). Performing repetitive movements with Thera-Band has previously been used as a way to induce muscle fatigue (Tsai et al., 2003). One end of the band was tied to a fixed anchor, located near the floor behind the subject’s standing position. The subjects were asked to grasp the other end with the arm along the body and then reach out completely at shoulder height (i.e., 90° shoulder flexion combined with complete elbow extension). While performing this movement, subjects were required to supinate their forearm on odd repetitions, and to pronate on even. The
speed of the movements was controlled by a metronome which was set at 60 beats per minute; subjects had to reach forward on one beat, then move back, on the next one. Each set of exercise lasted for one minute (30 reaches per set) followed by a 30s rest period. Thus, while the number of movements in each set was identical for all, the total number of sets performed by each subject depended on their assessment of fatigue. During the 30 s rest period between each set, participants were asked to rate their perceived exertion on the Borg CR-10 scale (Borg et al., 1987). They continued with sets of fatiguing exercises until one of the following conditions were met: they reported a Borg scale rating of 8 or higher, or they could no longer fully extend the arm for three consecutive movements. These conditions were unknown to the subjects before they initiated the fatiguing exercise.

Following the fatiguing exercise, subjects were repositioned at the same location in front of the reach target using the markings on the floor, then repeated the initial position sense trials for 10 reaches to each of the three target orientations, as described above. It has been shown that the changes in EMG activity (Kirsch & Rymer, 1987; Miller et al., 1987) and metabolic environment (Sahlin et al., 1997) accompanying fatigue are restored within 10 min. Therefore we completed the second position sense testing of all subjects within 4–6 min after the fatiguing protocol.

**Kinematics**

We used a motion analysis system (Vicon, Oxford Metrics ltd., Oxford, UK) to record the endpoint position and orientation. The reliability and validity of Vicon system have been well established before (Henmi et al., 2006). Two markers were placed at both ends of the block, equidistant from the center, to measure block and infer endpoint position and orientation. Marker position was captured (120 Hz) using six high-resolution infrared cameras.

**Borg Scale**

In this experiment, the qualitative measurement of fatigue was done using the Borg scale (Borg et al., 1987). The localized Borg CR-10 scale has been widely used to measure perceived task difficulty in both healthy and clinical (Noble, 1982) populations. More specifically to our study, the Borg CR-10 scale has demonstrated good reproducibility and sensitivity to change (Grant et al., 1999), acceptable reliability (Lagally & Costigan, 2004) as well as good validity with respect to physiological markers of fatigue, including cardiovascular (Chen et al., 2002); heart rate (Borg et al., 1987) aerobic power (Eston et al., 2006), oxygen consumption (Goss et al., 2003), blood and muscle lactate (Noble, 1982; Borg et al., 1987). Further, a good correlation (0.68–0.76) between Borg ratings and mean power frequency of the EMG signal has previously been shown in tasks that target upper trapezius muscle fatigue (Hummel et al., 2005), and in a recent study, Borg CR-10 ratings have been shown to be good predictors of endurance time in trapezius isometric contraction efforts (Troiano et al., 2008). This scale consists in a 0–10 point scale where 0 is “nothing” and 10 means “cannot continue”. A rating of 8 usually corresponds to a “very difficult task” and has been considered as an indicator of fatigue (Cote et al., 2002).
Electromyography

The presence of fatigue was also evaluated offline through electromyographic (EMG) analysis. The EMG data of six shoulder and arm muscles were recorded using bipolar (inter electrode distance (IED) = 2cm), Ag-AgCl surface electrodes (Ambu, Glen Burnie, Maryland, USA) with a telemetric system (Noraxon, Scottsdale, Arizona, USA). Data were filtered (bandpass: 10–500Hz), sampled at 1080 Hz and recorded throughout the fatiguing exercises. The electrodes were placed in the middle of muscle bellies of anterior, middle and posterior deltoid, biceps, upper trapezius and pectoralis major. The skin on each muscle was shaved if necessary and rubbed with alcohol before the attachment of electrodes.

Follow-Up Experiment

After completion of the main experiment, and to confirm that the observed changes were indeed due to the muscle fatigue and were not the effect of time, we performed a follow-up experiment with six other subjects (5 males, 1 female, mean age 25 ± 2.7). These subjects underwent the same experimental procedure as described above, except for the fatiguing phase. Instead of performing the fatiguing exercise, these subjects sat quietly for an equivalent amount of time (10 min; equal to the average fatiguing time in the main experiment).

Data Analysis

The purpose of the EMG recording in this study was to confirm the fatigue status of the muscles at the end of the fatiguing exercise. When a muscle is fatigued, the amplitude of its EMG signal increases (Kramer et al., 1987). Therefore, to determine the changes in EMG amplitude, these signals were first rectified and a linear envelope was created using a low pass filter with cut-off frequency of 5Hz (5th order Butterworth filter). Then the EMG signal corresponding to each fatiguing movement against the elastic band was identified; we computed the surface area of the EMG signal for each fatiguing movement. During the fatiguing exercise, subjects performed sequences of 30 repetitions. The total number of sequences was variable and depended on the subjective assessment of fatigue. Therefore for each of six recorded muscles, we computed the mean area under the curve for the first and the last sequence of fatiguing movements in all subjects and compared them with a dependent $t$ test. A Bonferroni adjustment (Jaccard & Wan, 1996) was then applied to the results of the $t$ test and the significant level was set at 0.0083.

The performance of subjects in the reproduction of an endpoint position was measured by computing both the linear and rotational changes in endpoint position. The linear changes were calculated from the mean coordinates of the two markers placed on the wooden block. Rotational changes or changes in endpoint orientation were obtained by computing the angle between a line connecting the two markers on the block and the vertical. Both of these variables were measured at the end of movement, i.e., when the subject was steadily holding the wooden block on the target.

In a few pilot tests before the main experiment, we found that during reaching to the target in the absence of vision in the pre fatigue condition, subjects tended
to make systematic errors, i.e., their mean endpoint position was systematically deviated with respect to the true target location. This type of error has been reported earlier for reaching movements (Prablanc et al., 1979; Prablanc et al., 1986). Because of this visuo-motor bias, we did not compare the subject’s endpoint position with the actual target’s position and orientation. Instead, we used each subject’s linear and rotational endpoint coordinates during the prefatigue task as their baseline and compared the changes that happened after fatigue. Specifically, we subtracted the pre fatigue values of position and orientation from those obtained postfatigue.

For the post/pre fatigue changes in endpoint position, we compared each mean of up/down and mediolateral positions separately using two-way ANOVAs (prepost fatigue × orientations). Rotational changes were also compared for all subjects using repeated-measures ANOVA (3 orientations × 2 conditions [pre and post fatigue]). We also compared the variability (between-trial standard deviation) of endpoint linear and rotational positions using two-way ANOVAs. Tukey post hoc comparisons were employed when appropriate. Effect size for significant results was reported as partial eta-squared.

**Results**

A significant increase in the signal amplitude seen by the end of exercise was considered to indicate fatigue in the muscle. In average, subjects developed fatigue after 6 sets (SD: ±3) of exercise lasting in total 10 min (SD: ±5). Figure 2A shows an example of EMG signal for the first and last fatiguing exercise in medial deltoid. Using a dependent t test with a Bonferroni adjustment, in four out of six recorded muscles, the EMG signal amplitude was shown to be significantly greater by the end of the exercise compared with the beginning, across the group (p < .008). These were the upper trapezius (p ≤ .005) and anterior (p ≤ .001), middle (p ≤ .001) and posterior (p ≤ .003) deltoids, which increased by averages of 39, 43, 44, and 35%, respectively (Figure 2B).

The analysis of endpoint positions in each direction (up/down, mediolateral) for all subjects showed a significant main fatigue effect in the vertical (up/down) direction (p ≤ .001, effect size = 0.11) with a greater trend for subjects to reach higher after fatigue (Figures 3 and 4). This change in vertical direction was the resultant of change in movement trajectory, from initial to final position (Figure 5). However, no significant effect was found in the mediolateral direction (p ≥ .8 for the main fatigue effect, achieved power = 0.05). The results also showed no significant change in the endpoint rotational coordinates after fatigue (p ≥ .7 main fatigue effect, achieved power = 0.08) (Table 1).

Finally, the comparison of inter trial standard deviation before and after fatigue showed a significant main effect of fatigue for endpoint position (p ≤ .03, effect size = 0.09), with post hoc analysis showing an increase in variability for up/down direction (p ≤ .04). There was also a significant fatigue × orientation interaction effect for rotational variability (p ≤ .0001, effect size = 0.4), with post hoc analysis showing a decrease in variability with fatigue at -35° (post hoc p ≤ .009), no change at the neutral vertical orientation (post hoc p ≥ .06) and an increase in variability at +35° (post hoc p ≤ .005) (Table 1).
Figure 2 — Results of the fatiguing exercise on EMG activity. A) The EMG activity (rectified envelopes) of the medial deltoid increased at the last set of fatiguing exercises for a single representative subject. The mean signal amplitude (dotted line) increased at the end of the exercise B) Average increase in signal amplitude for 6 muscles across all subjects. Significant increase was observed in 4 muscles. The error bars represent standard deviation.

Figure 3—Final endpoint position. The figure illustrates the distribution of the endpoint position (frontal view) at the two testing times for one subject. 95% confidence ellipses are indicated for each condition (pre and post). (Y: up/down position coordinates; X: mediolateral position coordinates)
Figure 4—Mean change in endpoint position. The figure shows the mean change in endpoint position for each subject, with respect to mean position before fatigue (0, 0). Error bars indicate standard error (Y: up/down position coordinates; X: mediolateral position coordinates).

Follow-Up Experiment

In the group of subjects who repeated the proprioceptive twice but separated with a rest period instead of a fatiguing exercise, the analysis of the changes in endpoint positions showed no significant difference, neither in the mediolateral \((p \geq .58, \text{ achieved power } = 0.08)\) nor in the vertical (up/down) direction \((p \geq .1, \text{ achieved power } = 0.3)\). The results also showed no significant change in the endpoint rota-
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<th>Table 1</th>
<th>Kinematic Outcome Measures Before and After Fatigue.</th>
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<td><strong>orientation</strong></td>
<td>-35°</td>
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<tr>
<td>vertical position (mm) §</td>
<td>-59.9 ± 58</td>
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<tr>
<td>Mediolateral position (mm)</td>
<td>-109.3 ± 11</td>
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<tr>
<td>Vertical position variability (mm) §</td>
<td>58.7</td>
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<tr>
<td>Mediolateral position variability (mm)</td>
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<tr>
<td>Endpoint Orientation (°)</td>
<td>-34.7 ± 3.7</td>
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<td>Endpoint orientation variability (°) *</td>
<td>3.7</td>
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§ significant fatigue effect

* significant interaction effect
tional coordinates \( (p \geq .93, \text{ achieved power} = 0.05) \). The comparison of inter trial standard deviation before and after the resting period also showed no significant difference in the variability, neither in the endpoint position \( (p \geq .32, \text{ achieved power} = 0.06) \) nor in the rotational coordinates \( (p \geq .54, \text{ achieved power} = 0.08) \).

**Discussion**

The purpose of this experiment was to estimate the extent by which muscle fatigue alters the position sense of the upper limb in healthy adult subjects. To date, few experiments have investigated the effect of fatigue on position sense in a multijoint task. Typically in a free multijoint task, different muscles and joints contribute the task. Therefore, different strategies might be employed to compensate for the compromised position sense at the fatigued joint. We were interested to see the difference in position sense after fatigue while such possible compensations may exist. In addition, our position sense measurement was based on subjects’ visual memory in a way that they were asked to reach to a previously seen target with eyes closed. This was different from most of the previous muscle fatigue studies, which examined the position sense based on subjects’ proprioceptive memory.

To measure muscle fatigue, most of the previous studies have employed a protocol based on maximal voluntary contraction (MVC) (Voight et al., 1996; Allen & Proske, 2006) and a few have used subjective measure (Borg scale) (Tripp et al., 2004; Tripp et al., 2006). Indeed, a decrease in MVC is taken as a sure sign of fatigue (Vollestad, 1997). MVC, however, is inconvenient in the case multijoint movements, as were performed in this experiment, due to difficulty in stabilizing the body parts not involved in the static contraction. The presence of fatigue was instead assessed during the experiment using a valid subjective measure (Borg scale), and was confirmed a posteriori through a statistically significant increase in EMG activity during the performance of the fatiguing exercise. Previous research has shown that the Borg scale is correlated with other physiological markers of fatigue, such as heart rate (Borg et al., 1987) oxygen consumption (Goss et al., 2003) and mean power frequency of EMG activity (Hummel et al., 2005).

We recruited 7 males and 5 females for our experiment. Pederson et al. (1999) compared kinesthesia in the shoulder between men and women, both at baseline and after muscle fatigue. They found that at baseline, women’s ability to detect the initiation of movement in the limb was weaker than that of men. However, the effect of muscle fatigue was found to be the same for both genders. In another experiment, Bjorklund et al. (2000) initially reported that muscle fatigue had significantly more effect on position sense in women compared with men. However, this group later published a critical comment on their own work to retract this finding based on methodological issues (Bjorklund et al., 2003) pointing to the controversy around this question. Thus, based on the equivocal findings in the existing literature on gender differences in terms of proprioception acuity, we conducted our experiment with the assumption that muscle fatigue may have similar effects on both genders. Other studies with larger gender subsamples will need to be conducted to better position the scientific literature on this question.

We inferred the position sense of the right upper limb by examining the ability of subjects to reproduce their endpoint position and orientation after a bout of
repetitive exercise that fatigued the arm musculature. Since participants did not have any visual or tactile feedback about their performance, we considered that any change in endpoint position or orientation would be indicative of an alteration in position sense. Indeed, participants only saw the reach target at the start of the trial, while their arm was positioned alongside their body. Because vision was blocked before movement initiation, they could then only rely on proprioceptive feedback to execute the reach movement.

The design of this study was a paired prepost design. Therefore we compared the change in subjects’ performance due to fatigue. Yet one of the limitations of the study was the lack of a control group. To address this possible limitation, we performed a follow-up experiment with 6 other subjects performing the same testing protocol except for the fatiguing phase, which rather included a period of quiet rest, equal in duration to the average fatigue period for the experimental group. The result of the follow-up experiment showed no change in subjects’ performance after a period of resting. This result supports the interpretation that the changes seen in the main fatigue experiment were indeed cause by muscle fatigue and not by any other factors solely related to time.

There are different hypotheses regarding the underlying causes of change in position sense in the presence of fatigue. Some authors believe that the malfunction of joint and muscle receptors may contribute to the change in position sense (Voight et al., 1996). However, other authors (Proske, 2005) believe that another factor, which they term the sense of effort, could play a role in providing erroneous feedback to the CNS. The sense of effort combines our perception of the heaviness of objects and the muscle contraction we generate (McCloskey, 1981), which is linked to the sense of fatigue in a way that the decline in muscle effectiveness due to fatigue is compensated centrally by an increase in motoneuron activity, which eventually leads to a progressive increase in the perceived effort (Proske, 2005). The exact origin of the sense of effort is controversial. Traditionally, the perception of effort is believed to arise from a “corollary discharge”, a neurological discharge from the motor to the sensory cortex (McCloskey, 1981). However more recent studies suggest that the sense of effort arises somewhere upstream and not simply from the motor cortex (Carson et al., 2002; Proske et al., 2004).

In this experiment, we found that the linear endpoint position in the up/down direction was significantly higher after fatigue. In fact, the majority of subjects (75%) tended to move their endpoint position upwards with respect to their pre-fatigue position. Allen & Proske (2006) reported that in an elbow matching task when the forearm is fatigued, the muscles produce less force, thereby requiring more effort to maintain a given arm position against gravity. Therefore the shifting of the endpoints to an upper position in our experiment could be due to the extra effort that subjects made to move their arm to the target against gravity, which caused them to overestimate the height of the target position. In addition, no change in mediolateral position after fatigue may be related to the fact that the EMG of pectoralis major, as the main shoulder adductor, was not affected by fatigue. Finally, We had set the target at the shoulder level. To reach to the target, subjects had to elevate their shoulder to an approximate angle of 45°. This approximate angle was constant for all subjects. Suprak at al. (2006) reported that the shoulder elevation repositioning error linearly decreases from 30° to 90° and increases again after 90°. Therefore in 45°, the position sense error should be at an acceptable level, neither
too high nor too low. If we had tested position sense at different shoulder angles, we’d had probably observed different results.

The target in this study was presented in three different orientations. Overall, the effects of fatigue on endpoint rotation angle were equivocal. The group analysis revealed no systematic changes across subjects. This could be due to the unconstrained, multijoint nature of our reaching task where subjects were able to employ different strategies and muscle combinations to reach to the targets. For example, if the shoulder position sense became less accurate due to fatigue, subjects could compensate with other joints like elbow and wrist, which likely were not fatigued and therefore able to compensate for fatigued muscles, and employ a different reaching pattern. On the other hand, as one of the limitations of this experiment, we could not record the EMG signal of all the muscles of the upper limb, making us incapable of judging the fatigue status in all muscles. Therefore the malfunction of receptors at the fatigued site might have been compensated by other receptors, especially the ones in the wrist and fingers. This type of movement compensation has already been shown in a few studies suggesting that subjects tried to involve more joints and muscles in the presence of muscle fatigue to do the required task correctly (Cote et al., 2002; Cote et al., 2005; Cote et al., 2008; Fuller et al., 2008). In the present experiment, similar strategies might have helped subjects to align their hand correctly with each orientation.

We found that the linear variability (standard deviation of linear endpoint positions) in up/down direction was increased after fatigue. Variability is a common feature of human movements that may play a role in the central organization of voluntary movements (Latash et al., 2002). The presence of variability in body movements makes them more flexible and stable, which may be interpreted as decreasing the chance of injury (Mathiassen et al., 2003). However, the increase of variability beyond its optimal value makes the neuromuscular system noisier and less adaptable (Stergiou et al., 2006) and consequently more susceptible to injuries. In goal-directed tasks, compensatory strategies can prevent such an increase in variability by employing non fatigued muscles (Gates & Dingwell, 2008) whereas in other tasks where subjects are not aware of the accuracy of their performance, the variability increases (Cignetti et al., 2009). Possibly in our experiment, since the subjects were not informed of their performance, they could not compensate for the fatigue and therefore their movement variability increased.

In addition, for rotational variability, we found a significant fatigue × orientation interaction, with a post hoc analysis showing different patterns of change for each orientation. In particular, we observed an increase in rotational variability for orientation +35°. To replicate this orientation, subjects had to supinate their forearm and externally rotate their shoulder. The posterior deltoid, as one of the external rotators of the shoulder, was found to be significantly fatigued after the exercise. Therefore, the observed increase in variability at this orientation can be related to the presence of fatigue in this muscle. This result is also consistent with the previous findings of Lee et al. (2003) who found that after shoulder muscle fatigue, position sense was only affected in the direction of external rotation. On the other hand, the rotational variability of orientation -35 was decreased after fatigue. Since the pectoralis major, as the internal rotator of the shoulder was not significantly fatigued after the exercise, we concluded that subjects’ movement in this direction became more consistent with multiple repetitions, thus reducing the movement variability.
Much has been said about the negative effects of muscle fatigue in the literature. Fatigue can increase the prevalence of bone strain and fracture (Yoshikawa et al., 1994) and increase the susceptibility of muscular and ligamentous injuries (Lorentzon et al., 1988; Pinto et al., 1999). In addition, many clinical conditions (e.g., heart failure, kidney failure, inflammatory myopathies, chronic arthritis, and aging) have been shown to be associated with muscle wasting and fatigue (Allen et al., 1995; Ahern & Laver, 1998; Balog et al., 2000). Many have also found that fatigue can alter the proprioception in the shoulder and make it prone to injuries (Voight et al., 1996; Lephart & Jari, 2002; Tripp et al., 2007). However, fatigue has some positive effects too. It has been suggested that the reduced neural drive leading to fatigue during intensive exercise may be a protective mechanism to prevent organ failure if the work was continued at the same intensity (Bigland-Ritchie & Woods, 1984). Moreover, Rooney et al. (1994) demonstrated that subjects who trained by repeatedly lifting a weight without resting experienced a significant increase in strength compared with subjects who trained with rest between exercises. Both groups developed muscle fatigue during exercise, but the fatigue level in the no-resting group was twice that of the resting group. Therefore the authors suggested that the processes, which bring about muscle fatigue during high-intensity exercise, provide a stimulus which brings about increases in strength. The results of such experiments imply that muscle fatigue should not be avoided at all times and at all costs. The decision about avoiding muscle fatigue or letting it occur depends on the goals of the exercise and should be made by a professional. For example in athletic training, where increase in muscle strength is needed, reaching to a degree of fatigue seems to be necessary but in a clinical setting where the goal of the exercise is the treatment of the patient, muscle fatigue should be treated with more caution. Where development of muscle fatigue is inevitable, incorporation of neuromuscular training to the regular exercise might help enhance proprioception and possibly prevent injuries.

**Conclusion**

The results of this study showed that the position sense of the upper extremity can be changed in the presence of fatigue. When position sense is altered in a joint, the likelihood of instability is increased (Lephart & Henry, 1996). An unstable joint is more susceptible to muscular and ligamentous injuries (Robinson et al., 2002; Robinson et al., 2006). Therefore fatigue should be considered as an important factor in the rehabilitation of musculoskeletal injuries, particularly in exercise therapy. Clinicians may use fatigue measurement tools to assess the fatigue level of the patients during the treatments. Furthermore, increasing the muscular endurance and fatigue threshold in athletes should be considered as a preventive strategy during training.

**References**


Muscle Fatigue and Position Sense


