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Neck muscle fatigue affects performance of an eye-hand tracking task

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ABSTRACT

Altered afferent input from the neck due to fatigue alters upper limb proprioception and is likely to impact upper limb performance accuracy. This study examined the effect of cervical extensor muscle (CEM) fatigue on eye-hand tracking accuracy in healthy participants.

Twenty-four healthy right-handed individuals were randomly assigned to either a control or CEM fatigue group. Each participant performed a tracking task which required shoulder rotation to move a circular object to a square target on a touchscreen computer. The task was performed with vision of the target and with the target hidden. A prone lying position, CEM fatigue protocol required participants to hold a 2 kg weight against gravity with their head in a neutral posture. The control intervention rested for 5 min, in a prone position, with the head supported in a neutral posture. Participants performed 3 trials with vision and 3 without at 5 different time points: (1) pre-intervention (fatigue or control), (2) immediately post-intervention, (3) 5 min, (4) 10 min, and (5) 20 min post-intervention.

There were significant differences between the target with vision and the hidden condition for both groups between pre- and post-fatigue trials in angle of trajectory ($p = 0.0001$), and distance from release point to the target ($p = 0.0001$). Significant differences occurred in the hidden target condition for the fatigue group immediately post fatigue ($p = 0.018$) for distance from release to the target.

Neck muscle fatigue reduced the accuracy of an upper limb tracking task to a hidden target, suggesting that altered afferent input from the neck due to fatigue may impair body schema and result in decreased upper limb performance accuracy.

1. Introduction

Humans rely on visual and proprioceptive information to inform planning and control of upper limb movement (van Beers et al., 1996). These sensory inputs are matched against the brain's internal map or "body schema" to predict the future position of the limb. In the absence of visual feedback, muscle spindles are responsible for limb proprioception in 3D space (Proske and Gandevia, 2009). The efficacy of limb proprioception is altered by sustained periods of movement performed in the absence of vision (Brown et al., 2003). When a target is visible, the result of reaching movements are more accurate (Proteau et al., 2000). However, participants are able to point to visual targets when the hand is occluded, indicating that proprioceptive information from the hand can relate its position to visually encoded positions. This suggests that the spatial position of the observed hand is encoded using both types of sensory information to enable accurate arm movements (van Beers et al., 1996).

Changes in sensory input from the neck may alter the body schema and lead to joint position sense (JPS) errors. Individuals with neck muscle stiffness have increased error when performing an elbow JPS task (Haavik and Murphy, 2011). Neck muscle stiffness (Haavik and Murphy, 2011) or fatigue (Zabihhosseinian et al., 2015) can alter sensory inputs to the CNS. The presence of neck muscle tension seems to alter the body schema, which represents spatial and/or temporal awareness of limb proprioception in 3D space (Haavik and Murphy, 2011). Recent work found that CEM fatigue, even for a short period of time, may alter cervical spine stability and modulate the cervical flexion relaxation ratio by decreasing the ability to relax the cervical extensor muscles as measured via surface electromyography (EMG). In this work, the EMG would have recorded the more superficial layers of the CEM (trapezius, splenius capitus and splenius cervicis) and possibly the middle layers of longissimus capitus and cervicis (Zabihhosseinian et al., 2015). CEM fatigue also altered upper limb proprioception, reducing the ability to accurately replicate elbow and forearm positions (Zabihhosseinian et al., 2015). Movement of the head and neck may trigger vestibular signals that alters interpretation of spatial coordinates

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for the arm (Knox et al., 2006) and passive displacement of the head and neck has been found to influence the accuracy of elbow and forearm proprioception (Knox and Hodges, 2005). Additionally, applying vibration to neck muscles without tilting the head also influences upper limb proprioception (Knox et al., 2006), demonstrating that altered neck afferent input, in the absence of vestibular changes, influences spatial awareness and alters upper limb proprioception (Knox and Hodges, 2005). Evidence has suggested that altered neck sensory input alters sensory feedback from the neck muscles to the CNS, and this can alter the map or schema of the upper limb in relation to the neck (Knox and Hodges, 2005). Therefore, if alterations in sensory input from the neck influences the internal body schema, this may have significant implications on upper limb motor control. However, the effects of CEM fatigue have not been studied in relation to an upper limb tracking task that predominantly relies on proprioception. There is currently a lack of understanding if altered proprioception induced by CEM fatigue translates to a reduction and worsening of motor performance.

The sense of movement generated by muscle spindles can be disturbed by muscle fatigue (Allen and Proske, 2006). Severe fatiguing activities affect both force- and position-matching tasks (Allen and Proske, 2006) by changing the amount of muscle activity needed to produce the required force to maintain limb position. Altered neck sensory inputs due to CEM fatigue can alter the map or schema of the upper limb in relation to the neck (Knox and Hodges, 2005). However, it is currently unknown how altered sensory feedback from the neck, due to CEM fatigue, impacts performance of an upper limb motor task which relies on an accurate body schema. Therefore, the objective of this study was to examine the influence of CEM fatigue on the performance of an upper limb tracking task performed with vision of a target and with the target hidden in order to increase the reliance on upper limb proprioception. We hypothesized: (1) eye-hand tracking performance would be reduced in the hidden versus vision target condition before CEM fatigue, (2) CEM fatigue would further impair performance in the target-hidden condition immediately following fatigue, with no impairments in performance in the vision condition, and (3) The fatigue group would show a slow recovery in performance over time, whereas the control group would show sustained improvements immediately following the control intervention.

2. Methods

2.1. Participants

Two groups of 12 healthy right-handed individuals participated (Fatigue: 6 Male, 6 Female; Control: 7 Male, 5 Female). Handedness was confirmed by the Edinburgh Handedness Inventory (EHI) (Cohen, 1961), and the Neck Disability Index (NDI) was administrated to confirm the absence of neck pain (scores of 0–4/50) for inclusion in the study (Vernon, 2008), (Table 1). This study was approved by the University of Ontario Institute of Technology Research Ethics Board.

Table 1
Participant demographics and self-report measures.

	Fatigue Group (6 Females- 6 Males) Mean (SD)	Control Group (7 Females- 5 Males) Mean (SD)	T-test alpha results
Age (years)	20.5 (2.1)	20.76 (0.9)	$t(11) = -0.3, p = 0.8$
Height (cm)	166.3 (10.3)	168.1 (6.1)	$t(11) = -0.7, p = 0.5$
Weight (kg)	68.9 (13.7)	63.3 (11.2)	$t(11) = 1.2, p = 0.3$
NDI score	2.3 (1.9)	2.7 (1.97)	$t(11) = -0.3, p = 0.8$
EHI score	72.7 (30.4)	59.7 (16.2)	$t(11) = 1.4, p = 0.2$
Time to fatigue (min)	5.1 (1.1)	5 min neck muscle rest	
Handedness	12 right handed	12 right handed	

2.2. Instrumentation

2.2.1. Electromyography

Muscle activity was measured bilaterally from the CEM using wireless surface electromyography (sEMG) (Trigno™, Delsys Inc., Boston, MA, USA) in keeping with a recent publication (Zabihhosseinian et al., 2015). The skin was prepared prior to the electrode placement by shaving and cleaning the site with an isopropyl alcohol swab. Parallel-bar surface electrodes with a 10 mm inter-electrode distance were secured with double sided tape (20–450 Hz, CMRR 92 dB @ 60 Hz, input impedance 10^{15} Ω) and Hypafix tape™ was applied over each electrode. Electrodes were placed bilaterally 20 mm lateral to the space between the spinous processes of C4 and C5 in line with fiber orientation and over the muscle belly of the CEM. All sEMG data were sampled at 2000 Hz.

2.2.2. Position tracking software

Custom software (Unity™, San Francisco, CA) was used to create the tracking task. The software required participants to track a circular object to a square target on a touchscreen computer with discrete movement for each trial. Path deviation was measured as the angle from the desired trajectory and distance from release of object to the target. The circle radius was 50 pixels (e.g. 1.32 cm on the large monitor), the square width was 100 pixels (2.64 cm) and the minimum distance between start and end locations was 15.87 cm. This size was selected as the minimum size found in pilot testing that was clearly visible to all the participants, when sitting at an arm's length distance away from the monitor. Object kinematics (pixel data)) were sampled at 60 Hz.

2.3. Experimental procedures

2.3.1. General overview

Upon arrival to the laboratory, participants gave their informed written consent, then were randomly assigned to either the control or fatigue group. 13 females and 11 males were randomly assigned to either the control or fatigue intervention by flipping a coin. In order to ensure gender balance between groups, the coin toss was performed separately for each gender, and once a group was full (12 participants), the remaining participants were then allocated to the other group.

Both groups completed two practice trials, where they received instructions regarding proper arm and finger movement. After practice, participants performed the first set of the pre-intervention eye-hand tracking task. Next, the fatigue group completed the CEM fatigue protocol, while the control group rested their head and neck on a head rest. Participants performed the eye-hand tracking task immediately, 5 min (min), 10 min, and 20 min post-intervention.

2.3.2. Position tracking task

Participants were seated on a height adjustable chair. For each trial they were told to use their index finger to position the circular object at the center of a square target using a fully extended arm, which required movement at the shoulder joint in the transverse plane, either: (a) with vision of the target, or (b) with the target hidden (Fig. 1). The position of the square target was kept the same, but the position of the circular object was randomized to ensure unpredictability throughout the eye-hand tracking task. For the hidden target condition, the square was not visible. For both vision and hidden conditions, the trajectory of dragging from the circular object to the square target was visible.

Between trials, the screen returned to the reference frame and participants placed their hand back on the table with the forearm at approximately 90–100 degrees of elbow flexion (dependent on participant). Care was taken to keep the head and neck in a neutral and balanced position during the tracking task. All participants were familiarized with the experiment with two practice trials during which they received instructions regarding proper arm and finger movement,

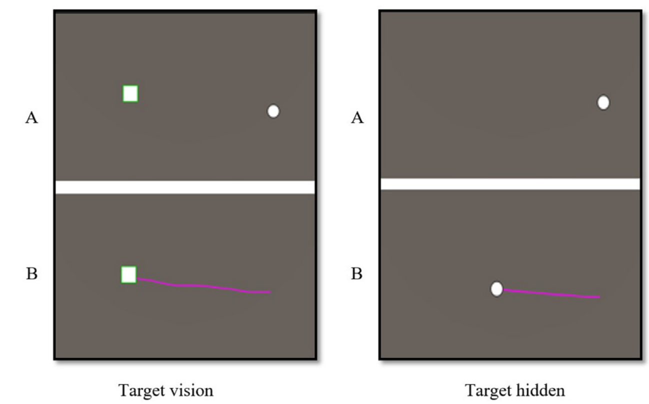

Fig. 1. Eye-hand tracking task. View of computer screen during the start and end of each movement track. Participants moved their index finger from right to left to keep the circular object at the center of a square target for each trial. This was performed: (A) with target vision, and (B) target hidden guidance.

and path tracking.

Vision vs hidden condition: Each trial consisted of two tracking movements where participants had vision of the target (target in vision) followed by three trials where the target was not visible (target hidden) and therefore participants had to rely on proprioception to move their limb to the remembered target position. Each participant performed the blocks of five trials (2 vision and 3 hidden) at five different time points in relation to the intervention (fatigue or control), time points included: (1) pre- intervention, (2) immediately (imm.) post-intervention, (3) 5 min, (4) 10 min, and (5) 20 min post-intervention.

2.3.3. Fatigue/control protocol

CEM Fatigue Protocol: Participants randomly allocated to the fatigue group, performed an initial warm up session with 10 repetitions of neck flexion, extension, lateral flexion, and rotation to both sides. The CEM fatigue protocol has been shown to have a good test-retest reliability (Edmondston et al., 2008, 2011). Prior to fatigue, participants lay prone on a table with their arms alongside their trunk and their head/neck supported in a comfortable neutral position by a headrest located on the table edge. To ensure that participants were primarily using CEM to maintain head position during the fatigue task, a counter-support strap was fixed around the thorax at the level of T6. A Velcro strap was fixed around the head and an inclinometer (Carpi digital angle gauge™, Carpi tools, Pomona, California) was placed superior to the right ear to measure sagittal head position. A 2 kg weight was hung from the head, and the fatigue protocol began by removing the head support from under the head, and participants were required to hold the head in a horizontal position with the chin retracted (Fig. 2). The CEM fatigue test was terminated when participants could no longer maintain the head posture due to discomfort or fatigue, or if the horizontal position of the head changed by more than 5 degrees towards the floor (from the starting position) for more than 5 s.

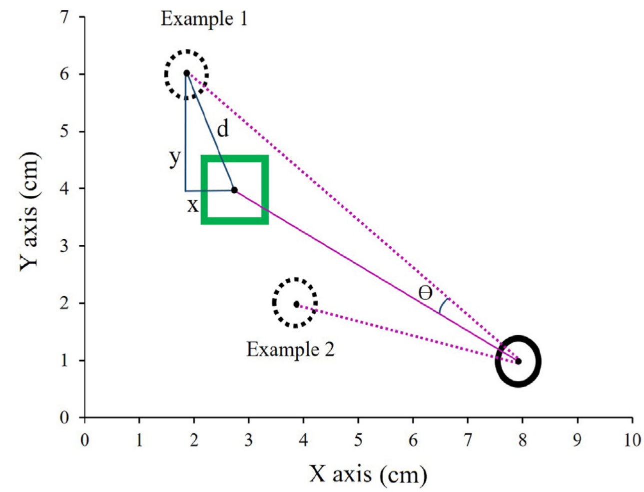

Fig. 3. Example of two hand-path tracking trajectories. The green square represents the target and the solid circle is the starting point. The dotted circles are two examples of the end point. For example 1, θ is the angle of the trajectory and d is the distance from release to the target location with consideration of error for both X and Y axes.

CEM Control Protocol: The control participants lay prone for 5 min on a padded table with their head supported on a head rest over the end of the table and arms alongside their trunk (Fig. 2).

2.4. Data analysis

Myoelectric measures of fatigue were measured as mean power frequency (MNF) and root mean square (RMS) of the CEM sEMG during the first and last 10 s of the fatigue protocol (Fast Fourier Transform length, 1-s; window type, Hanning; window length, 0.13 s; overlap, 0.06 s were calculated, using the Delsys EMG works Analysis 4.1.1.0 Calculation Toolkit) (Zabihhosseinian et al., 2015). Task error was measured in pixels, as how far away the center of the circle was from the center of the square. The angle of trajectory and distance from release to the target location were measured as the angles of path deviation and end-point position in relation to the target. The X- and Y-axis deviations were calculated based on these measures to quantify if there was directional specificity (Fig. 3). These dependent measures were calculated separately as averages for the target vision and target hidden movements within each of the five blocks pre- and post-intervention (CEM fatigue or control). Since every participant had different baseline values, data for angle of trajectory, distance from release to target, and direction of error were normalized for each participant by dividing each of these measures by the respective baseline values.

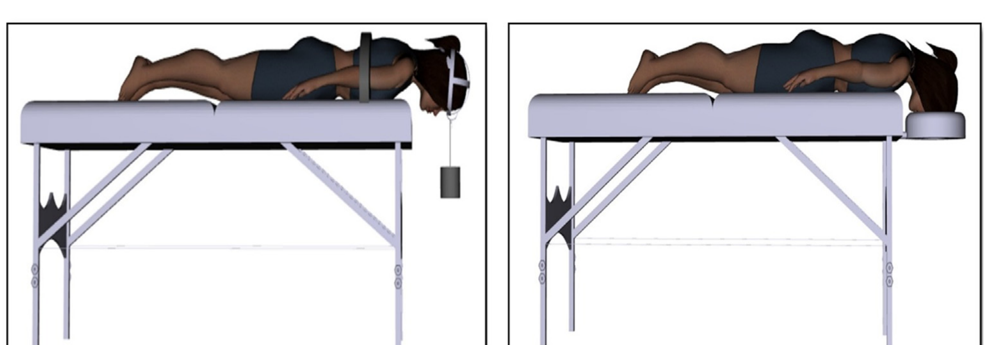

Fig. 2. Submaximal fatigue/control protocol: (Left) Participant performing fatigue protocol. (Right) Control participant prone on a padded table for 5 min.

2.5. Statistical analysis

Baseline differences between groups: Independent samples t-tests compared baseline values for the fatigue and control groups for age, height, weight, NDI, and EHI. Repeated measures analysis of variance (ANOVA) with Vision vs Hidden as the repeated measure and group (fatigue vs control) as the between subject factor were run on the baseline pre-intervention data in order to confirm differences in performance between the vision and hidden conditions based on previous literature (Proteau et al., 2000), and possible differences between groups.

Myoelectric measures of fatigue: Fatigue was defined as an inability to hold the in a neutral position. To ensure that physiological fatigue had occurred and that participants had not terminated the test due to motivation or other factors, MNF and RMS were examined using a 2×2 repeated measures analyses of variance (ANOVA) with fatigue (pre vs post) as the repeated measure and CEM (right and left) as the between subjects factor. Since all participants were right hand dominant, the left-right comparison examined if there were differences in physiological fatigue between the two sides.

Effects of fatigue: It was determined that the vision and hidden conditions were significantly different at baseline, in terms of distance from release to the target location, angle of trajectory, and path deviation. Therefore, separate two-way repeated measures ANOVAs were performed following the intervention, with time period (pre and post-fatigue) as the repeated measure, and group (fatigue vs control) as the between subjects factor. Pre-planned contrasts evaluated the overall repeated measures ANOVA to compare the two groups (fatigue vs control) at each time point. Since the X and Y axis deviations were calculated based on angle of trajectory and distance to endpoint (Fig. 3), repeated measures ANOVAs on the X and Y axis directions were performed only if there was a significant difference in one of these outcomes measures. This would allow for an understanding or directional specificity to the error.

Statistical significance was set at $P \leq 0.05$ for all analyses (SPSS v.24, IBM Corporation,

Armonk, NY, USA). All numeric values are expressed as mean ± standard deviation.

3. Results

3.1. Participants

Demographics of the control and fatigue groups are summarized in (Table 1).

There were no significant differences in demographics between groups. The mean baseline NDI and EHI scores for both the fatigue and control group confirmed that all participants were free of neck pain and strongly right-hand dominant.

3.2. Fatigue protocol

For the fatigue group, the mean isometric contraction time to fatigue was 5.14 ± 1.08 min, which was similar to the 5 min rest period for the control group. A decrease in MNF (Öberg et al., 1990) and an increase in RMS amplitude (Öberg, 1995) are characteristics of the EMG signal indicative of muscle fatigue. Post-fatigue MNF was significantly lower than baseline for both right and left CEM ($F_{1,\ 22} = 56.29$, $p = 0.0001$), with no significant interaction between right and left CEM ($F_{1,\ 22} = 2.18$, $p = 0.154$). Post-fatigue RMS amplitude was significantly greater than baseline for both right and left CEM ($F_{1,\ 22} = 7.781$, $p = 0.011$), with no significant interaction between right and left CEM ($F_{1,\ 22} = 2.533$, $p = 0.126$).

3.3. Baseline pre-intervention differences between vision and hidden conditions

The repeated measures ANOVA for the non-normalized baseline data with Vision vs Hidden as the repeated measure and group (Fatigue vs Control) as the between subject factor confirmed that:

Distance from release to the target location: There were significant differences between the vision and hidden condition ($F_{1,22} = 144.06$, $p < 0.0001$), and a significant interaction between the control and fatigue groups ($F_{1,22} = 6.808$, $p < 0.016$), with vision being significantly more accurate.

Angle of trajectory: There were significant differences between the vision and hidden condition ($F_{1,22} = 26.528$, $p < 0.0001$), with vision being significantly more accurate, with no differences between the two groups ($F_{1,22} = 0.700$, $p = 0.412$).

Distance from end-point to the target (X, horizontal direction): There were no significant differences between the vision and hidden condition ($F_{1,22} = 1.918$, $p = 0.180$), and no significant interaction between the two groups ($F_{1,22} = 0.440$, $p = 0.514$).

Distance from end-point to the target (Y, vertical direction): There were no significant differences between the vision and hidden condition ($F_{1,22} = 0.552$, $p = 0.465$), and no significant interaction between the two groups ($F_{1,22} = 0298$, $p = 0.59$).

The comparison of the normalized data for each variable is as follows:

3.4. Distance from release to the target location

In Vision condition: Following the intervention (fatigue or control) there was a significant overall effect of time ($F_{1,22} = 201.37$, $p < 0.0001$), but no interaction between groups (fatigue vs control) in the vision condition ($F_{1,\ 22} = 0.002$, $p = 0.961$) (Fig. 4A).

Hidden condition: There was a significant effect of time ($F_{1,22} = 132.79$, $p < 0.0001$) and a significant interaction between groups (fatigue vs control) in the hidden condition immediately following fatigue ($F_{1,22} = 6.541$, $p = 0.018$) (Fig. 4B), with the control group improving their performance to a greater extent. The pre-planned contrasts between groups indicated similar trends at both 5 min post ($p = 0.066$) and 10 min post ($p = 0.06$).

3.5. Angle of trajectory

In Vision condition: There were no significant changes in the angle of trajectory over time ($p = 0.329$) and following the intervention (fatigue vs control) there was no significant interaction between groups ($F_{1,\ 19} = 0.919$, $p = 0.350$) (Fig. 5A).

Hidden condition: Following the intervention (fatigue vs control) there was no significant interaction between groups for angle of trajectory in the hidden condition ($p = 0.102$). The pre-planned contrasts to baseline indicated that the fatigue group had significant improvements in the hidden condition immediately post intervention ($F_{1,\ 19} = 6.963$, $p = 0.016$), 10 min post intervention ($F_{1,\ 19} = 2.938$, $p = 0.045$) and 20 min post intervention ($F_{1,\ 19} = 10.138$, $p = 0.005$) relative to baseline (Fig. 5B). Although, still better than baseline, performance was decreased 5 and 10 min post-fatigue relative to the immediate post-fatigue trial, followed by much better performance for the 20 min post-fatigue trials (nearly zero error).

3.6. Distance from end-point to the target (X, horizontal direction)

In Vision condition: Following the intervention (fatigue vs control), there was a significant main effect of time ($F_{1,\ 22} = 6.36$, $p = 0.019$), but no significant interaction between groups ($F_{1,\ 22} = 1.468$, $p = 0.219$) (Fig. 6A).

Hidden condition: There were no significant time interactions ($F_{1,\ 22} = 0.915$, $p = 0.459$) and no significant interaction between groups

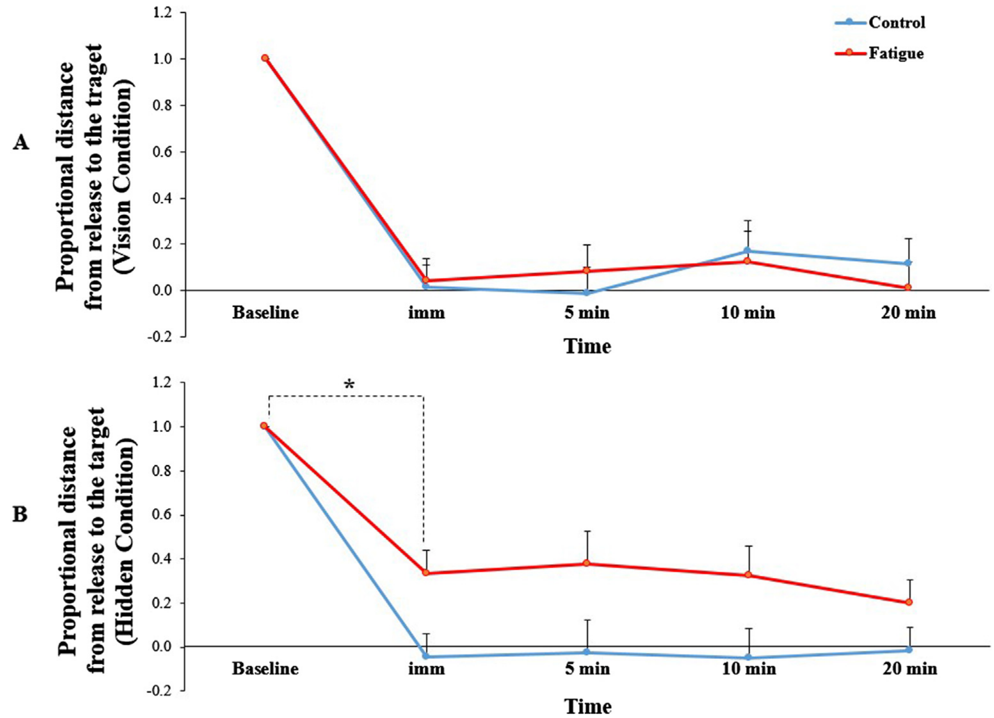

Fig. 4. Normalized distance from release to the target location (all distances are normalized to baseline). (A) Vision and (B) Hidden target conditions for both control and fatigue groups between baseline and post intervention trials. Error bars represent the standard deviation of the mean. *Significance of $p \leq 0.0001$.

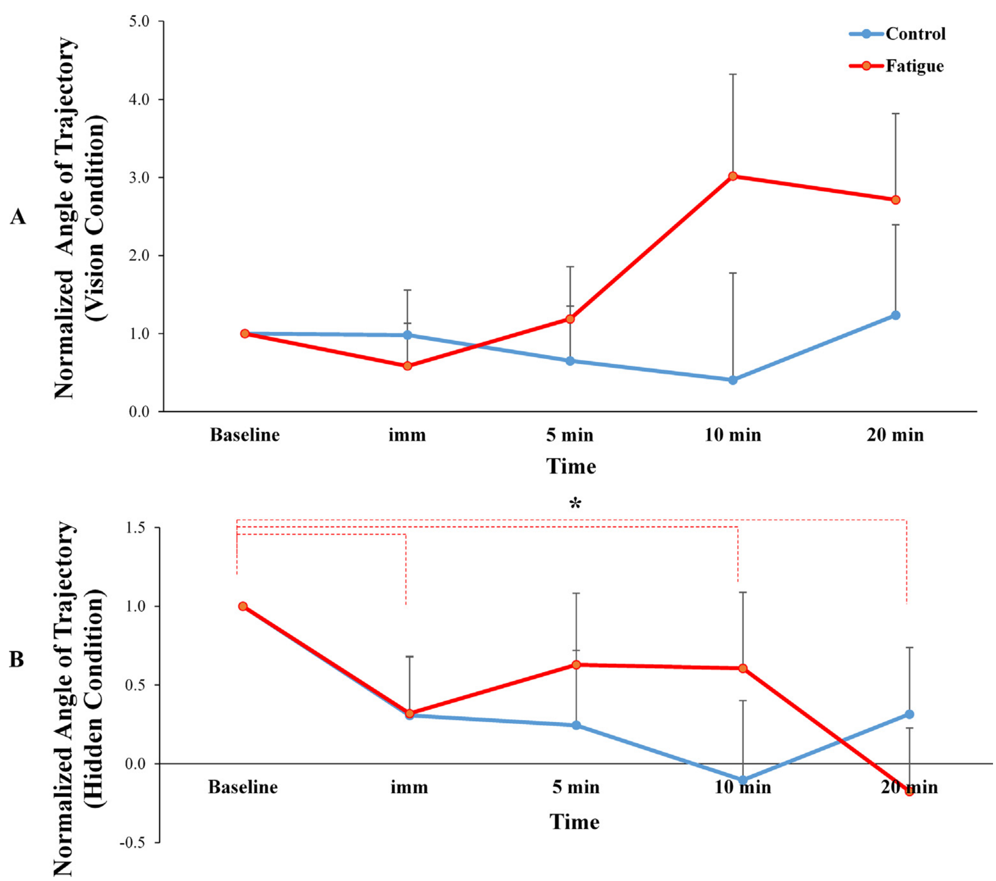

Fig. 5. Normalized angle of trajectory in vision and hidden target conditions for both control and fatigue group (all angles are normalized to baseline). Error bars represent the standard deviation of the mean. *Significance of $p \leq 0.0001$.

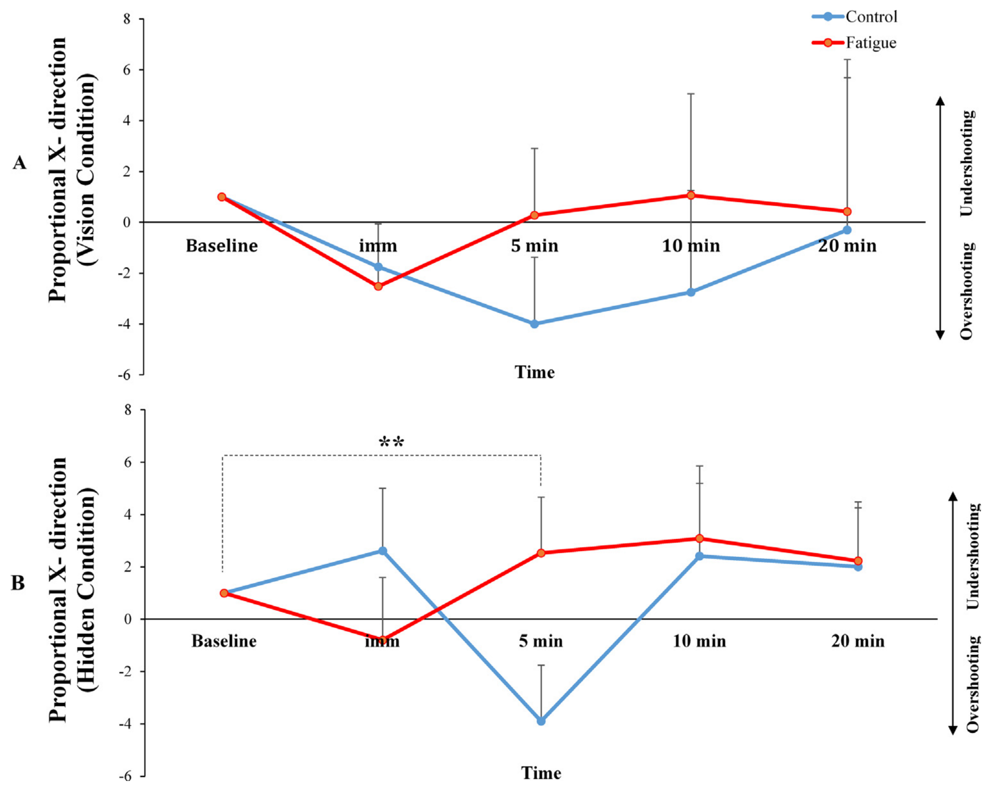

Fig. 6. Distance from end-point to the target (X, horizontal direction). Negative refers to overshooting the target, and positive under shooting the target. **Significance of $p \leq 0.05$.

(fatigue vs control) ($F_{1,}$ 22 = 1.871, p = 0.185) (Fig. 6B). There was a significant interaction between groups (fatigue vs control) from baseline to 5 min post intervention ($F_{1,\ 22} = 4.518$, $p = 0.045$). The fatigue group overshot the target in the immediately post intervention trials and this trend switched to the opposite direction (undershoot), in the 5 min post intervention trial (Fig. 6B), with performance remaining almost similar for the remaining trials.

3.7. Distance from end-point to the target (Y, vertical direction)

In Vision condition: There were no significant changes over time ($F_{1,\ 22} = 1.041$, $p = 0.556$) and no significant interaction (fatigue vs control) between groups following the intervention (fatigue vs control) ($F_{1,\ 22} = 1.187$, $p = 0.322$) (Fig. 7A).

Hidden condition: Following the intervention there was no significant interaction between groups ($F_{1,\ 22} = 0.323$, $p = 0.862$). The fatigue group showed a slow recovery and the control group showed improvement immediately in the hidden condition, however there was no significant differences between groups over time with performance remaining almost similar (Fig. 7B).

4. Discussion

This study investigated the effect of an eye-hand tracking task on sensorimotor processing and the interactive effects of CEM fatigue on task performance. Baseline differences were found between the vision and hidden target conditions for the fatigue and control groups in distance from the target and the angle of trajectory. Fatigue altered the distance from release to the end-point with a significant interaction between groups and this was evident from baseline to immediately post-fatigue in the hidden condition. In addition, there were no significant impairments in the vision condition for any outcome measures. Moreover, we found differential changes in the hidden target condition at different time points for angle of trajectory and in the X-direction distance from release point. This was in accordance with our hypothesis that the fatigue group would show a slow recovery and the control group would show improvements immediately following the control intervention during the hidden target condition.

People tend to create straight and smooth hand movements when reaching for an object, and both proprioceptive and visual feedback contribute to the global control of these hand trajectories (Scheidt et al., 2005). However, vision is not always available for movement planning or for providing online feedback about limb position in space during the trajectory (e.g. reaching for a light switch in a dark room) (Sergio and Scott, 1998). The visual and proprioceptive responses work together during hand-path control and final position guidance of tracking and reaching movements (Scheidt et al., 2005). In the absence of a visual predictable target trajectory, hand movements are linked to the internal predictor model that integrates eye movements into consequent hand motor performance, and the internal model of eye movements can transfer to the hand with the same latency (Miall and Reckess, 2002). Information from the limb is necessary for accurately adjusted movement and to specify the patterns of muscle contraction for the subsequent maintenance of the posture (Ghez et al., 1990). The baseline differences between the vision and hidden target conditions is predicted because the hidden condition relies on an accurate body schema. This is consistent with a previous study which reported that sighted individuals with a blindfold had an increased error in hand-path curvature direction when compared with their own visually guided movements and with congenitally blind participants (Sergio and Scott, 1998). One possible explanation is that misperception of the tracking path influenced by the sensory systems used to plan and guide movement direction, and loss of target position on the hidden condition, altered the motor patterns to execute the limb movements (Sergio and Scott, 1998).

Our results demonstrated that the accuracy of the distance from release to the end-point of the tracking hand-path was affected by the CEM fatigue immediately post-fatigue. This suggests that the altered

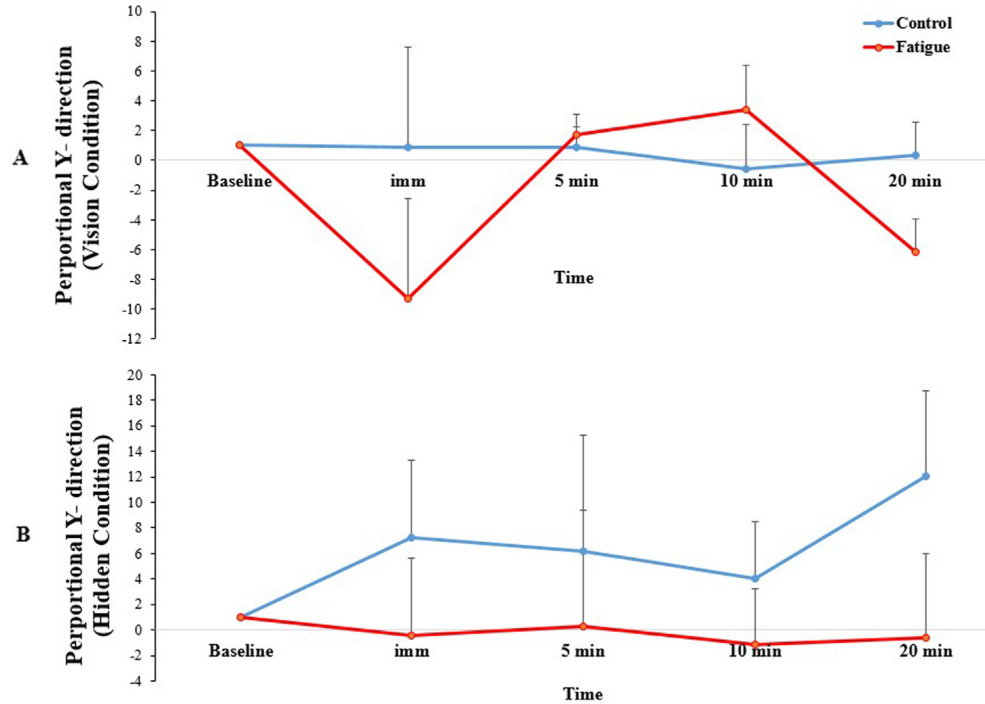

Fig. 7. Distance from end-point to the target (Y, vertical direction) for (A) vision and (B) hidden target conditions. Negative refers to the end-point being below the target, and positive being above the target.

neck input impaired upper limb proprioception, which consequently altered the tracking path. Muscle fatigue, even for a short period of time, may alter cervical spine stability by transferring loads to the passive tissues and substantially increasing muscle activity (Zabihhosseinian et al., 2015). Fatiguing the CEM alters firing of group I to IV afferents, and decreases firing of Ia afferents (Macefield et al., 1991). Muscle fatigue increases involuntary discharge in mechanically sensitive non-spindle group II and III muscle afferents and alerts their reaction for 20–30 s subsequent to fatigue (Hayward et al., 1991). CEM fatigue has been shown to alter upper limb proprioception (Zabihhosseinian et al., 2015) and impair neck muscle motor control as measured by the cervical flexion relaxation response (Zabihhosseinian et al., 2015). Therefore, our findings are important, as they indicate that input from the neck also affects upper limb movement performance. Altered afferent input from the neck to the CNS is likely to lead to a distorted body schema, which then impacts spatial and/or temporal awareness of limb movement in 3D space (Haavik and Murphy, 2011). Neck muscle fatigue may alter body schema and sensorimotor integration, resulting in inaccurate upper limb performance (Knox and Hodges, 2005).

In the distance from release to the end-point and angle of trajectory, there was a trend in hand path direction at both 5 min and 10 min post-fatigue for a continued decrease in performance for the fatigue group in the hidden condition, indicating that the altered input due to fatigue was impacting the accuracy of upper limb performance. The accuracy of the hand path was affected by the CEM fatigue but as we predicted, a potential practice effect may account for increased accuracy throughout the trials. This coincides with the idea that training improves joint proprioception sensitivity (Lee et al., 2003); however, it may also be due to participants becoming more familiar with the task, along with recovery from the fatigue during the course of the trials. This further confirms that our findings are really due to the CEM fatigue, since with an absence of fatigue, we would have expected either greater improvement or no change.

In the immediate post fatigue trials, we found that participants did overshoot the target in the X- direction during the hidden condition and undershoot the target during the vision condition. These results are consistent with a previous study, which reported that without visual feedback, hand location tends to drift over time (Brown et al., 2003). In the absence of visual feedback, a gradual decline occurs in the ability of the proprioception sense to signal limb position by decreasing the accuracy of movement distance and direction over a series of movements (Brown et al., 2003). Vision to some extent can substitute for proprioceptive feedback when afferent neural pathways are compromised (Sainburg et al., 1995). Afferent feedback from limb proprioceptors are enough to guide performance of almost straight and smooth tracking hand movements (Scheidt et al., 2005). This can happen even in the complete absence of prior visual experience as when blindfolded (DiZio and Lackner, 2000) or when visual feedback is removed when moving to a target position, as in the case of the current study. Thus, the impaired tracking performance following fatigue in the hidden target condition suggests that CEM muscular fatigue impacts upper limb tracking performance, by affecting the relationship between the neck and upper limb in the overall body schema.

Motor memory is a component of the process of improving a specific motor task through repetition, while motor prediction refers to estimating future states of a system. (Wolpert and Flanagan, 2001). Motor prediction estimates how the arm will move in response to a motor command, relative to the environment, which is termed an internal forward model (Wolpert and Flanagan, 2001), i.e. the ability to perform a task by predicting the dynamics of a body part (Ito, 2008). The CNS, in order to plan motor commands for a movement, relies on both forward and reverse models, which are the result of coordination of both visually observed consequences of the motor command, and its proprioceptive feedback (Mehta and Schaal, 2002). During constrained target tracking, joint stiffness is increased to improve accuracy of the movement (Selen et al., 2006). In a 2007 study, participants tracked a sinusoidal moving target by performing elbow flexion and extension in the horizontal plane pre and post elbow flexor and extensor muscle fatigue by resisting against a time varying motor torque. To control for the learning effect, the tracking task performance was retested 5 min after muscle fatigue. The fatigue caused participants to change their control strategy to a feedforward strategy during tracking and they stayed closer to the center of the target than in the unfatigued state

(Selen et al., 2007). In the current study, the fatigue group showed slower performance recovery and less improvement in motor learning in the presence of CEM fatigue compared to the control group. Because the target location was able to be visualized for the first 2 trials of each block, it suggests that the impaired performance in the hidden condition relate to changes in an internal body schema, rather than an inability of motor memory to remember the target location.

Neck muscles have a high density of sensory receptors with neural connections to the vestibular and oculomotor systems (Jull et al., 2007; Winters et al., 2012). Altered neck sensory input, due to neck pain or neck fatigue, can alter upper limb motor performance (Helgadottir et al., 2010; Zabihhosseinian et al., 2015) and alter the body schema of the upper limb in relation to the neck (Johnson, 2001; Knox and Hodges, 2005). Previous work found that neck fatigue impacted elbow proprioception, adding support to the concept that altered afferent input from the neck can distort the body schema of the upper limb in relation to the neck (Zabihhosseinian et al., 2015), similar to the Knox and Hodges study (Knox and Hodges, 2005). The fact that neck fatigue impaired performance accuracy in the hidden condition of the current study demonstrates that the altered proprioception seen previously (Zabihhosseinian et al., 2015), also leads to worse performance on an upper limb tracking task that is reliant on accurate upper limb proprioception.

5. Conclusion

This study confirms that CEM fatigue can influence the accuracy of an eye-hand tracking path, possibly due to an altered body schema. Immediately after fatigue, there was a significant increase in the distance from the release to the end-point for the hidden target. This suggests that altered afferent input, in an absence of visual guidance from the neck following fatigue, may impair upper limb proprioception and consequently alter eye-hand tracking path. These findings are important as they indicate that input from the cervical spine affects upper limb movement performance. These outcomes indicate that attention needs to be given to neck posture and muscle fatigue during upper limb rehabilitation and to occupations which require precise upper limb movements with the neck in an awkward posture or at risk of fatigue (e.g. mechanics, surgeons, and dentists). Future work is needed to confirm findings and explore whether body representation or motor efference is responsible for these effects.

Conflict of interest

None of the authors has any conflict of interest.

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Appendix A. Supplementary material

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