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Cervical flexion–relaxation response to neck muscle fatigue in males and females

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ABSTRACT

In this study the effect of muscle fatigue on the cervical spine flexion–relaxation response was studied. Twenty healthy participants (10 males and 10 females) were recruited for data collection. The Sorenson protocol was utilized to induce neck muscle fatigue. Surface electromyography and optical motion capture systems were used to measure neck muscle activation and head–neck posture, respectively. A post-fatigue reduction in the Flexion–Relaxation Ratio (FRR) and higher FRR for females compared to males were observed. A post-fatigue decrease was also observed in the onset and offset angles resulting in an expansion of the myoelectric silence period. Gender had no effect on the onset and offset angles of the silence period. Post-fatigue shift in the onset and offset angles and the expansion of the silence period indicate an increased contribution by the passive viscoelastic tissues in stabilizing the cervical spine under fatigued condition.

1. Introduction

The work-related musculoskeletal disorders (MSDs) of the neck or cervical spine put a substantial burden on the health and economics in many industrialized countries. Recent U.S. Bureau of Labor Statistics (BLS) data indicate that work-related neck pain requires a median of 11 days away from work to recuperate compared to 5 days for all other body parts combined (BLS, 2012). The symptoms of neck pain often last for prolonged periods of time and reoccurrence is observed for 50–80% of people within five years after the first occurrence (Côté et al., 2008). It is also estimated that about 67% of people suffer neck pain at some point in their life (Côté et al., 2004).

The etiology of neck or cervical spine MSDs is believed to be multidimensional, with physical work demands, psychosocial stress, and individual characteristics being the major contributing factors. Among the physical demands, work-related exposures such as sustained static postures, sub-maximal repetitive and forceful arm exertions are consistently identified as possible risk factors for cervical spine MSDs. Several studies have shown that the use of static and awkward head–neck postures leads to the fatigue of neck extensors (Finsen, 1999; Schüldt et al., 1986; Szeto et al., 2002). Repetitive arm and neck exertions are also known to contribute to the fatigue of the neck muscles (Chowdhury et al., 2013; Hagberg, 1981; Hansson et al., 1992). Some studies have also shown an active contribution by the neck muscles during forceful arm exertions leading to the fatigue (Kimura et al., 2007; Nimbarte, 2014; Nimbarte et al., 2012, 2013; Troiano et al., 2008).

Among the individual characteristics, gender has been consistently identified as a non-modifiable risk factor of MSDs of the neck (Hogg-Johnson et al., 2008). A higher prevalence of work-related neck pain was reported among females than males in several studies. In the United States, one year prevalence of neck pain among the general population was 40% for females compared to 29% for males (Bovim et al., 1994). A similar trend of higher prevalence of neck pain among females was also reported in the studies performed among Dutch, Swedish, and Japanese populations (Andersson et al., 1996; Guo et al., 2004; Picavet and Schouten, 2003). A higher prevalence of work-related neck pain for females was also reported in different working populations. Cagnie et al. (2007) reported an annual prevalence of 54.7% and 38.3% for females and males, respectively, among office workers. Fernandes et al. (2011) reported higher neck MSDs among females compared to males in a Brazilian plastics industry. Skov et al. (1996) reported a much higher prevalence of neck pain among the female (76%) sales workers compared to their male (54%) counterparts.

The muscle fatigue generated by work-related exertions and its interaction with gender may affect the biomechanical stability of the cervical spine. A less stable spine can be both a cause and

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consequence of spinal pain. Spinal stability is usually achieved through highly coordinated interactions of active and passive components of the neuromuscular system (Granata and Gottipati, 2008; Panjabi, 1992). The Flexion–Relaxation Phenomenon (FRP) explains the synergistic load sharing between these components. For the cervical spine, during head flexion, the cervical extensors gradually increase their activation to compensate for the increasing effect of gravity on the mass of the head. In the fully flexed posture, the strained viscoelastic elements generate forces sufficient to offset the effect of gravity, resulting in a reduced activation of the extensors (Meyer et al., 1993).

FRP in the cervical spine was first reported by Meyer et al. (1993). Consequently, other studies have evaluated the effect of factors such as load applied to the head, load carried using a backpack, trunk posture, computer use, and speed of movement on the load sharing between the active and passive tissues using cervical FRP (Lee et al., 2011; Pialasse et al., 2009, 2010; Yoo et al., 2011). A diminished FRP in individuals with symptoms of neck pain compared to asymptomatic healthy controls has also been observed in previous studies (Maroufi et al., 2012; Murphy et al., 2010). The main purpose of the current study was to quantify the post-fatigue changes in the stability of the cervical spine using the FRP. In addition, the role played by gender in the flexion–relaxation response of cervical spine due to the fatigue was also studied.

2. Methods

2.1. Participants

Twenty healthy adult participants (10 males and 10 females) were recruited to participate in this study (Table 1) from a pool of university students by posting advertisements on notice boards across the campus. The primary inclusion criteria required that the participants were free from any type of musculoskeletal, degenerative, or neurological disorders and had no history of neck, shoulder, and back injury or notable pain that required medical care over the last twelve months. All the participants gave their informed, written consent according to a protocol approved by the local Institutional Review Board.

2.2. Experimental protocol

A lab-based study was performed to study the effect of neck muscle fatigue on the cervical FRP. Neck muscle fatigue was induced according to the Sorensen fatigue protocol (Lee et al., 2005). Each participant lay prone on a table with arms to their sides and shoulders (acromion) level with the edge of the table (Fig. 1). The head and neck segments were exposed to gravitational forces to induce the neck muscle fatigue. A subjective scale (Borg CR-10 discomfort scale) was used to continuously monitor participant discomfort during the Sorensen protocol. The Sorensen protocol was discontinued when a score of 8 on the Borg scale was reached to prevent the risk of excessive fatigue or possible injury.

To study effect of fatigue on the cervical FRP, at least 3 head flexion–extension trials were recorded for each participant before and after the completion of the Sorenson protocol. These trials were performed in a seated posture. The upper body of the participants was stabilized in a seat using a four-point harness. Each head flexion–extension trial consisted of four phases (Fig. 2): (1) maintain neutral head–neck position for approximately 2 s; (2) fully flex the neck with the goal of approximating the chin to the upper chest (manubrium) within 5 s; (3) maintain full flexion for 5 s; (4) extend neck back to the neutral position within 5 s. A metronome with an audible tone (1 beat/s) was used to precisely control participants' movement during the different phases.

Table 1
Participants' demographic data.

Gender	Age (year)	Height (cm)	Weight (kg)
Female	29.1 ± 3.9	162.9 ± 6.3	56.2 ± 7.7
Male	24.1 ± 2.4	175.6 ± 6.3	70.5 ± 7.6
Total	26.6 ± 4.2	169.3 ± 9.2	63.4 ± 10.7

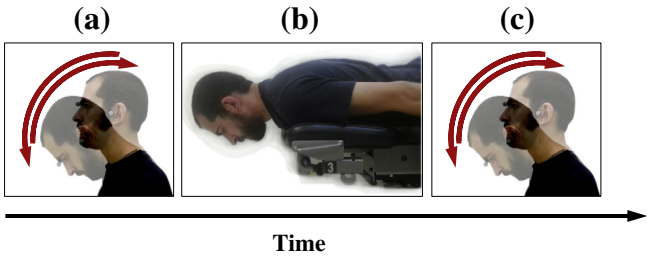

Fig. 1. Sequence of activities performed during the data collection: (a, c) head flexion–extension trials performed pre- and post-fatigue; (b) posture used during the Sorenson protocol to induce the neck muscle fatigue.

2.3. Instrumentation

The activity of the neck extensors during the Sorenson protocol and FRP trials was recorded using a Bagnoli-16 desktop surface electromyography (EMG) system with parallel bar-active surface electrodes (Delsys Inc., Boston, USA). The CMRR for the electrodes is 92 dB with input impedance greater than 10^{15} Ω. Two surface electrodes were placed bilaterally on the neck at the C4 level. The C4 level was determined as 2.5 times the distance between the C6–C7 vertebrae above the C7 level. The electrodes were placed parallel to the muscle fiber (approximately 35° to the vertical line between C7 and C4) (Nimbarte et al., 2010). The skin was prepared for electrode placement by shaving (if needed) and cleaning with 70% alcohol pads.

Head–neck kinematic data during the FRP trials were recorded using an eight-camera optical motion-capture system (Vicon Motion Systems, Oxford, UK). A set of three retro-reflective markers (14 mm in diameter) was used for the data collection. One marker was placed on the glabellas bone in the forehead area and the other two markers were placed on each side of the head at the proximal aspect of temporomandibular joint (TMJ). Vicon Nexus 1.8.1 software was used to record the kinematic as well as the EMG data. EMG data streams were synchronized with the motion data by acquiring the analog EMG data using a Vicon ADC (analog-to-digital converter) screw terminal box. The EMG and kinematic data were sampled at a rate of 1000 Hz and 100 Hz, respectively.

2.4. Data analysis

The EMG data recorded during the Sorenson protocol and the head flexion–extension trials were demeaned and full-wave rectified. The full-wave rectified EMG data were low pass filtered at 4 Hz using a fourth-order Butterworth filter to form a linear envelope (Burnett et al., 2007).

The endurance time during the Sorenson protocol varied between the participants. In one previous study, data recorded during the first minute were used in the analysis (Descarreaux et al., 2008). We believe that the data recorded during the middle part of the Sorenson protocol provide a better representation of the neuromuscular system's physiological status due to its adaptation to the prescribed exertion than the start or the end

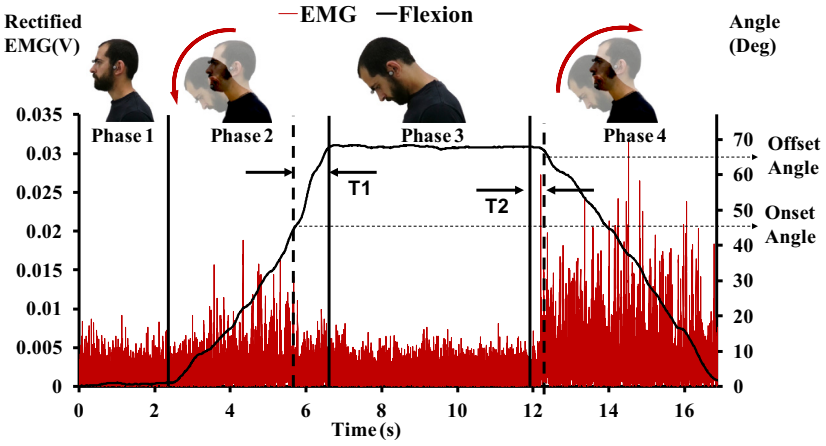

Fig. 2. Flexion–relaxation phases during a head flexion–extension trial and the corresponding FRP variables. Muscle activity data recorded using EMG is plotted using primary axis to the left and the head flexion–extension data is plotted using secondary axis to the right.

part. Therefore, to standardize the data selection across the participants, the EMG data recorded during the middle, or median, minute were used in the fatigue analysis. If the median-minute was not an integer then one of the two middle-pair minutes was randomly selected. A window size of 512 ms was used in the analysis. Sixteen non-overlapping windows were used in the analysis (total data length of 8192 ms). For each window, amplitude was quantified by obtaining the mean of low pass filtered data. In addition median frequency was also estimated for each window. Thus, sixteen amplitude and median frequency values from each individual participant were used in the fatigue analysis. The amplitude and median frequency values were normalized using the maximum values obtained within the sixteen windows.

The raw marker data were reconstructed, labeled, and gap filled in the Vicon Nexus software. Consequently, the XYZ coordinates of the markers were exported to quantify the head flexion–extension angle. The midpoint of the two TMJ markers was estimated. This point approximately represents the center of mass for the head. A vector from the midpoint of the two TMJ markers to the glabellas bone marker was defined. The orientation of this vector with the horizontal axis of lab-coordinate system was identified as the flexion–extension angle. Standard neutral head position was used to define the zero flexion–extension angle.

The processed neck EMG and head flexion–extension angle data were used to estimate the following FRP parameters:

(1) Flexion–Relaxation Ratio (FRR): The FRR quantifies the ability of the neck extensors to relax during forward flexion. It is defined as the ratio of the maximum EMG activation in the extension phase (phase 4) to the average EMG activation during the full flexion phase (phase 3) (Alschuler et al., 2009) (Fig. 2). A FRR $\geqslant$2.5 was used to identify presence or absence of FRP (Pialasse et al., 2009).

(2) Onset and offset angles: The onset angle corresponds to the flexion angle when the load sharing is transferred from the active muscles to the passive tissues. The offset angle corresponds to the extension angle when the load sharing is transferred back to the active muscles from passive tissues. Onset and offset angles were determined using the Instantaneous Flexion–Relaxation Ratio (IR_i) (Eq. (1)). The flexion angle corresponding to $IR_i < 40\%$ was defined as the onset angle, and the extension angle corresponding to $IR_i > 40\%$ was defined as the offset angle (Pialasse et al., 2009). The onset and offset angles were expressed as the percentage of maximum flexion angle.

$$IR_i = \frac{EMG_i}{\text{maximum EMG in Phase 4}} \quad (1)$$

where EMG_i is the instantaneous muscle activity at time i

(3) Silence period expansion: This is typically used to quantify the temporal changes in the myoelectric silence of the active tissues in fully flexed posture. Post-fatigue expansion of the silence period was estimated using the time differences between the onset angle and start of phase 3 (T1), and the end of phase 3 and offset angle (T2) (Fig. 2) using Eq. (2):

$$\text{Silence period expansion} = \text{Onset Shift} + \text{Offset Shift} \quad (2)$$

where

$$\text{Onset Shift} = T1_{\text{Post Fatigue}} - T1_{\text{Pre Fatigue}} \quad (3)$$

$$\text{Offset Shift} = T2_{\text{Post Fatigue}} - T2_{\text{Pre Fatigue}} \quad (4)$$

The start and end of phase 3 was determined when flexion angle fall two standard deviations below the mean. The mean and standard deviation were calculated using a moving window of 100 points.

2.5. Statistical analysis

A two-factor general linear analysis of variance (ANOVA) was performed to evaluate the effect of fatigue and gender on the FRP parameters. Fatigue was treated as fixed effect with two levels (pre and post). Gender was also treated as fixed effect with two levels (male and female). Participant was treated as a random factor nested in gender. The adequacy of the linear model was confirmed by normal probability plots of the residuals between the actual and fitted value. Significance level was set to 95%. Minitab 16 software (Minitab Inc., Pennsylvania, USA) was used to perform the statistical analysis.

3. Results

During the Sorenson protocol, the mean endurance time until muscle fatigue was 12.1 ± 5.6 min. Female participants showed a slightly higher (12.9 ± 6.6 min), but statistically insignificant (p-value = 0.535), endurance time compared to male participants (11.3 ± 4.0 min).

Mean EMG amplitude recorded during the middle minute of the Sorenson protocol increased at a rate of 0.9% and 0.26% for females and males, respectively (Fig. 3). The mean median frequency

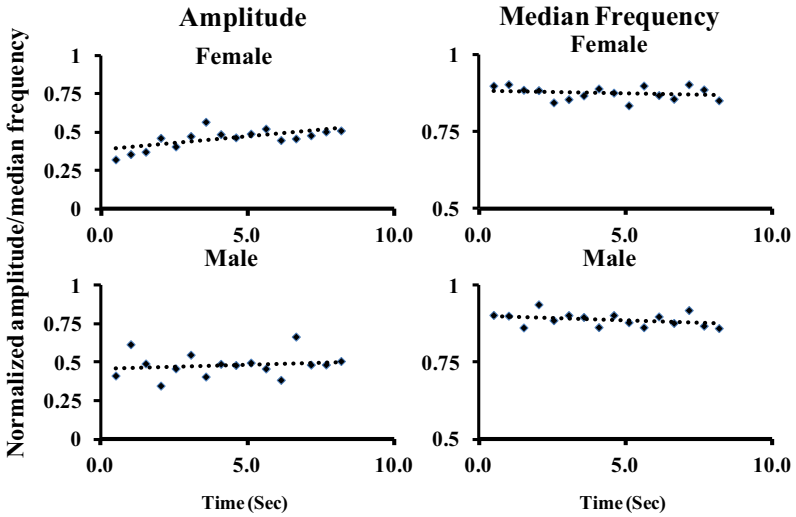

Fig. 3. Mean (across all participants) normalized median frequency and amplitude values fitted with linear regression curves.

showed a decline at a rate of 0.11% and 0.16% for females and males, respectively (Fig. 3).

Two hundred and forty head–neck flexion–extension trials were collected (20 participants, three trials per participant, right and left sides, pre- and post-fatigue). The FRP was observed in 234 trials, and was found to be absent post-fatigue in two female participants.

Statistically, the FRP parameters were found to not differ between the left and right sides. Consequently, the data were pooled from both sides for further statistical analysis. The effect of gender on the FRR was statistically significant. Females showed higher FRR than males (Table 2). For all other FRR parameters, the effect of gender was statistically insignificant.

The effect of fatigue on the FRP parameters was statistically significant (Table 3). The FRR was reduced significantly from 4.88 ± 0.81 pre-fatigue to 3.33 ± 0.57 post-fatigue (Table 3). Smaller onset and offset angles were observed post-fatigue. The onset angle decreased by about 16% and the offset angle decreased by about 5%. The time differences between the onset angle and the start of phase 2 (T1), and the offset angle and the end of phase 2 (T2) increased significantly post-fatigue. The T1 increased by about 71.4% and T2 increased by about 98.3%. These changes in the T1 and T2 caused the silence period to expand by about 86 centiseconds. This increase is equivalent to 17.2% (86/500), where 500 centiseconds is the average length of the silence period for all participants.

The fatigue–gender interaction was statistically insignificant for all FRP parameters (Fig. 4).

4. Discussion

The effect of fatigue and gender on the cervical FRP parameters was investigated in the current study. Fatigue produced a reduction in the FRR. A higher FRR was observed for females compared to males. The fatigue-gender interaction was insignificant for the FRR and the gender effect was due to the difference observed in the pre-fatigue FRR values. The pre-fatigue FRR values in females were about 14% higher than males compared to only 5% post-fatigue. Overall, EMG amplitude during the extension (fourth) phase in females was about 58% higher than males. This produced a higher FRR among females than males. Higher neck and shoulder muscle activation in females compared to males was also observed in a few previous studies (Johansen et al., 2013; Nordander et al., 2008). Lindman et al. (1991) reported that females possess lower functional capacity due to a smaller cross-sectional fiber area. Females also have a higher proportion of type I fibers (slow twitch) compared to males (Esbjörnsson-Liljedahl et al., 1999; Maher et al., 2009). The longer endurance time for females than males observed in the current study could be due to the higher proportion of fatigue resistant type I fibers present in females. Smaller cross-sectional fiber areas and fewer type II muscle fibers may result in a higher firing rate in females than males to meet a similar force demand. Augmented firing of type II fibers generate larger activation levels (Gamet et al., 1993) and perhaps may have been responsible for the increased extension phase activation and higher FRR among females.

Post-fatigue reduction in the FRR observed in the current study is congruent with the results of several previous studies (Lee et al., 2011; Maroufi et al., 2012). The activation level of the neck extensors during the relaxation (third) phase increased by about 20% post-fatigue, increasing the FRR. Fatigue reduces the muscle fiber excitation–contraction coupling (Allen, 2004; Kurebayashi and Ogawa, 2001) due to the accumulation of lactic acid and diminished calcium ion concentration. This enforces an augmentation of the motor unit firing rate to maintain similar levels of force exertion (Vukova et al., 2008). During the post-fatigue relaxation phase,

Table 2
Effect of gender on the FRP parameters.

FRP parameters	Male	Female	*p*-Value
FRR	3.89 ± 0.92	4.32 ± 1.12	0.05*
Onset angle (% full flexion)	74.50 ± 6.89	73.20 ± 7.51	0.223
Offset angle (% full flexion)	94.40 ± 3.00	94.70 ± 3.41	0.682
T1 (centiseconds)	122.05 ± 34.08	130.86 ± 46.33	0.226
T2 (centiseconds)	30.08 ± 12.32	28.92 ± 11.08	0.560
Expansion (centiseconds)	152.13 ± 44.32	159.78 ± 54.14	0.300

p-values marked by ∗ show statistical significance.

Table 3
Effect of fatigue on the FRP parameters.

FRP parameters	Pre-fatigue	Post-fatigue	*p*-Value
FRR	4.88 ± 0.81	3.33 ± 0.57	<0.001*
Onset angle (% full flexion)	80.20 ± 2.16	67.6 ± 4.07	<0.001*
Offset angle (% full flexion)	96.90 ± 1.34	92.2 ± 2.64	<0.001*
T1 (centiseconds)	93.18 ± 14.44	159.73 ± 28.46	<0.001*
T2 (centiseconds)	19.78 ± 3.16	39.23 ± 8.13	<0.001*
Expansion (centiseconds)	112.96 ± 14.81	198.96 ± 28.55	<0.001*

p-values marked by ∗ show statistical significance.

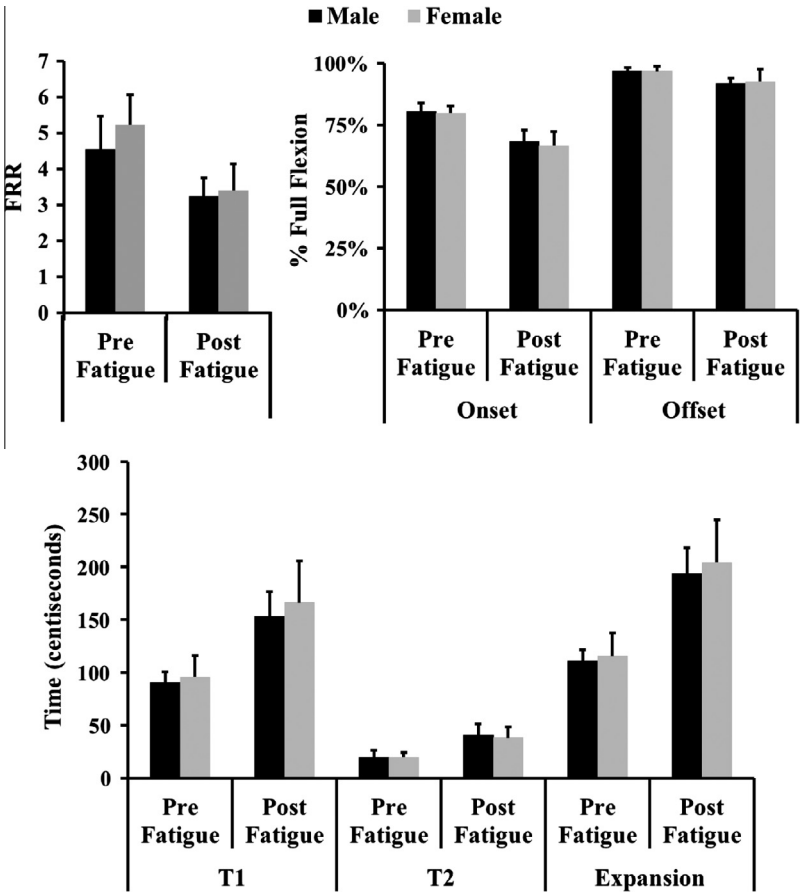

Fig. 4. Mean FRP parameters pre and post fatigue for the male and female participants. Error bars represent one standard deviation.

in order to counterbalance the head weight, an increased motor unit firing rate may have possibly increased the muscular activation and the FRR.

Gender had no effect on the onset and offset angles of the silence period. Similar findings were previously reported for the effect of fatigue on the FRP in the lumbar spine. Descarreaux et al. (2008) reported no significant difference in the onset and offset angles between males and females for the lumbar spine. Dickey et al.(2003) also reported similar findings when investigating the effect of cyclic flexion on the lumbar spine FRP. On the contrary, Solomonow et al. (2003) reported significant gender differences for the onset and offset angles when studying the effect of 10 min of static flexion on FRP parameters. Higher onset and offset angles were observed for females compared to males. The authors attributed this difference to the possibility of females developing more creep in the passive tissues than males. Creep induced elongation reduces passive tissues' ability to generate force required to sufficiently stabilize the spine. Consequently, during the FRP, a delayed shift in the load sharing to passive tissues and increased onset and offset angles were reported in previous lumbar spine studies (Shin et al., 2009; Solomonow et al., 2003; Youssef et al., 2008). On the other hand (muscle) fatigue negatively impacts the force generation ability of the muscles or active tissues and therefore an early shift in the load sharing to passive tissues and decreased onset and offset angles are observed in the current and previous lumbar spine studies (Descarreaux et al., 2008; Olson et al., 2004).

In the current study, the expansion of the silence period was estimated as the sum of onset and offset shifts. The lower onset angles observed after the fatigue increased the onset shift causing the silence period to begin at an earlier instance compared to the pre-fatigue condition. On the other hand, the lower offset angle increased the offset shift resulting in a delayed cessation of the silence period post-fatigue. The early onset of the silence period is an indicator that the fatigued cervical extensors were unable to maintain the forces required to stabilize the cervical spine and consequently shifted the load sharing to the passive tissues prior to the deep flexion. The delayed cessation of the silence period shows that the fatigued cervical extensors must have relied upon the deep cervical muscles to generate moment in the early extension (fourth) phase.

The onset shift was almost three fold the offset shift, indicating a more pronounced contribution by the passive viscoelastic tissues than deep muscles in stabilizing the cervical spine under fatigued condition. For the lumbar spine it has been proposed that the deep back muscles initiate trunk extension in the fatigued condition whereas the superficial muscles initiate trunk extension in the non-fatigued condition (Descarreaux et al., 2008). A very small offset shift observed in this study does not seem to fully support this notion for the cervical spine. On the other hand, it is also likely that the Sorenson protocol used in this study may have fatigued the deep muscles to some extent (perhaps lesser than superficial muscles) affecting their ability to generate the extension moment producing a narrow offset shift. Intramuscular recording would be required to further confirm deep and superficial muscle synergies pre- and post-fatigue.

Symptomatic individuals show diminished cervical spine FRP (reduced FRR) compared to symptom free individuals (Maroufi et al., 2012; Murphy et al., 2010). Results of the current study indicate that the fatigue also reduced the FRR. Although pain

symptoms and fatigue both produce reductions in FRR, the actual mechanism for the reductions may be different. Among symptomatic individuals, spinal instability caused by the damaged passive tissues has been proposed to produce persistent activation of the extensor muscles during the relaxation period to cause the reduction in FRR. Among symptom free individuals, results of the current study indicate that the increased muscular demand under fatigued condition produce the reduction in the FRR. An early shift in the load sharing to the passive tissues was also observed post-fatigue. Thus, symptomatic individuals, when exposed to fatiguing exertions, are expected to experience increased muscular demand if the symptoms are due to the damaged passive tissues. This may lead to early onset of fatigue and increased risk of injury.

5. Conclusions

The conclusion drawn from the results indicate that the neck muscle fatigue modulates the cervical spine FRP. Females exhibited higher FRR values than males but the fatigue–gender interaction was insignificant. Post-fatigue shift in the onset and offset angles of the silence period and the resulting expansion of the silence period indicate an early shift in the load sharing from the fatigued muscle to the passive tissues.

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