Journal of Electromyography and Kinesiology 11 (2001) 247–254

JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY

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Trunk muscle coactivation in preparation for sudden load

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Received 4 October 2000; received in revised form 11 December 2000; accepted 9 January 2001

Abstract

Biomechanical stability of the lumbar spine is an important factor in the etiology and control of low-back disorders. A principle component of biomechanical stability is the musculoskeletal stiffening generated by preparatory muscle coactivation. The goal of this investigation was to quantify preparatory behavior, evaluating trunk muscle activity immediately prior to sudden trunk flexion loading during static extension tasks compared to activity observed when subjects were informed no sudden load would occur. Coactive excitation was also examined as a function of fatigue and gender. Results demonstrated increased extensor muscle and flexor muscle coactivation following static fatiguing exertions, potentially compensating for reduced trunk stiffness. Female subjects produced greater flexor antagonism than in the males. No difference in the preparatory coactive muscle recruitment patterns were observed when subjects were expecting a sudden flexion load compared to recruitment patterns observed in similar static postures when subjects were informed no sudden load would be applied. This indicates the neuromuscular system relies greatly on response characteristics for the maintenance of stability in dynamic loading conditions. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Trunk; Stability; Muscle; Coactivation

1. Introduction

Tolerance to spinal injury can be dramatically influenced by musculoskeletal stability. Although NIOSH suggests spinal loads below 3400 N may be considered safe for a majority of the working age population [31] the spinal column will become unstable and fail at compressive loads less than 100 N without muscles to provide stability [8]. Fortunately, the neuromuscular system can control mechanical stability of the spine, thereby allowing the structure to safely withstand extreme compressive loads.

Increased muscle activation and antagonistic co-activation may be recruited to augment spinal stability in an unstable environment [7,11,14]. Empirical measurements suggest preparatory coactivation and intra-abdominal pressure reduced kinematic displacement following sudden flexion load, implying increased trunk stiffness associated with co-contraction [6,36]. Recent measurements demonstrate antagonistic coactivation is actively recruited in response to changes in stability [32]. Thus, in an unstable environment or when a sudden load is anticipated it is expected that increased co-contraction must be recruited to stabilize the spine in a pre-emptive manner to reduce injury risk.

Sudden load paradigms are designed to investigate the neuromuscular preparation and response to biomechanical trunk perturbations. When a sudden flexion load is unexpectedly applied to the trunk a response in the form of antagonistic co-activation has been reported at levels up to 140% of the equivalent static value [24]. The response is influenced by asymmetry, fatigue, and the subject's history of low-back pain [28,39]. Unfortunately, preparatory myoelectric behavior has been rarely reported. Measurements by Lavender et al. [23] revealed some subjects increased preparatory antagonistic co-activation while others demonstrated no preparatory myoelectric activity. Thomas et al. [36] reported that activity in both extensor and flexor muscles ramped up in time to meet the kinetic impact. Conversely, no preparatory myoactivation was observed when the timing of impact was unknown. It was curious that increased coactivation was not observed in both unblinded and blinded con-

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PII: S1050-6411(01)00003-7

ditions as the subjects were aware that a sudden load would occur in both conditions, but lacked timing information in the latter. Recognizing that coactivation augments trunk stiffness and stability, one might expect increased antagonism in preparation for both blinded and unblinded sudden loading conditions.

Preparatory coactive recruitment may be influenced by fatigue and gender. It has been established that fatigue influences muscle spindle behavior [27] and associated reflex mechanics including stretch sensitivity, electromechanical delay and myoelectric response amplitude [1,12,16]. Fatigue has also been shown to affect muscle response time in the low-back [39]. All of these factors modulate stability. Epidemiologic data support these biomechanical concepts, demonstrating correlations between risk of LBD and muscular endurance [2]. Thus, fatigue depression of neuromotor response may require compensation by means of modified preparatory myoelectric behavior to maintain spinal stability. Gender is also a risk factor with females suffering more than twice the rate of musculoskeletal and low-back injuries than equivalently trained males [10,22]. To improve gender inclusion in the workplace it is necessary to understand potential factors influencing biomechanical stability. Gender differences in passive joint stiffness have been established [4] and recent measurements indicate gender differences in muscle-controlled active joint stiffness [15]. To compensate for reduced active muscle stiffness, it is hypothesized that females may perform lifting tasks with greater coactivation to augment trunk stiffness and stability. The influences of fatigue and gender on preparatory myoelectric activity have not been reported.

The goal of this investigation was to quantify trunk muscle electromyographic (EMG) activity in preparation for a sudden flexion load. It was hypothesized that increased coactivation would be observed when subjects were preparing for an impending flexion moment impact compared to equivalent conditions wherein subjects were informed no sudden load was to be applied. Furthermore, it was hypothesized that increased preparatory coactivation must be observed in a fatigued state and greater coactivation may be demonstrated by female subjects to maintain biomechanical stability. Improved understanding of neuromuscular preparatory behavior may contribute to enhanced assessment of spinal stability and control of LBD risk.

2. Materials and methods

2.1. Subjects

Eleven males and 14 females, 19–40 years of age, with no prior history of low back pain voluntarily participated in this experiment. Mean (±SD) subject height and weight was 172.9±10.9 cm and 71.9±13.9 kg respectively. A secondary study included nine subjects, four male and five females, 21.2–26.0 years of age and mean (±SD) height and weight of 166.8±9.8 cm and 66.8±11.8 kg. All subjects provided informed consent approved by Human Investigations Committee of the university.

2.2. Protocol

EMG and motion data were recorded throughout a sudden loading event as subjects performed static trunk extension exertions. Subjects held a plastic crate (ht×wt×depth=28×33×33 cm) with weight inside and a cable attached to its base. The cable passed through pulleys to a location behind the subject where another weight could be dropped, causing sudden added tension in the cable and an abrupt downward load on the crate. The arrangement was designed so the subjects could not observe the sudden load, preventing knowledge of the impact timing. The sudden load weight was 2.5% of each subject's maximal lifting capacity dropped from 0.5 m. The sudden load weight magnitude was selected to avoid marked change in the static trunk moment before and after the impact while still providing a sufficient dynamic impulse to warrant a neuromuscular response.

Sudden loading events were performed in all possible combinations of expectancy, pre-load, task asymmetry, and fatigue. Sudden load expectancy was established by informing the subject prior to each trial whether a sudden load would be applied. Case weight (pre-load) was set at 0%, i.e. no added weight, and 20% of the subject's maximum voluntary exertion (MVE) strength in trunk extension. The MVE value was established from the maximum of three isometric exertions performed by pulling against a handle and cable attached to the floor via a load cell, with the cable length adjusted to create a 45° flexed posture. Sagittally symmetric sudden loading tasks were examined wherein the subjects maintained a static forward-flexed posture of 45° with the feet aligned with a transverse line on the floor. This was prescribed to simulate lifting postures observed in industry, to assure the crate held by the subjects could not rest on their thighs, and to apply a pre-load from the trunk mass flexion moment. Asymmetric tasks required the subject to maintain a static forward-flexed posture of 45°, holding the box in the sagittal plane while twisting such that the feet were aligned according to markings 45° to the left. Subjects were placed in the pre-designated posture, informed whether a sudden load would be applied, and when comfortable data collection began with the sudden load applied at a random time during the 10 s trial.

All six combinations of sudden load, pre-load and asymmetry were performed in an unfatigued state with a minimum of 2 min rest between exertions [3]. All conditions were repeated in a fatigued state. During the fatigued conditions no rest between exertions was provided so as to aid in the maintenance of the fatigued state. Fatigue was established by encouraging subjects to hold 20% of their MVE load with their trunk flexed at 45° degrees for as long as possible. When the subject could no longer hold the crate, the experimental trials were conducted. To assure the subject remained fatigued throughout all of the conditions, this process was repeated every 2 min, or after approximately four trials.

A brief secondary experiment was performed with nine volunteers. To investigate preparatory behavior in conditions with minimal pre-load, the secondary study was performed with identical independent conditions but with the subjects in an upright posture and the sudden load magnitude was increased to 5% MVC dropped from 0.5 m.

2.3. Dependent variables

EMG signals were collected at 1000 Hz using bipolar disposable surface electrodes (Medicotest, Rolling Meadows, IL) from four bilateral sets of trunk muscles. These muscles included the right and left recti abdominis (LRA, RRA), external obliques (LEO, REO), internal obliques (LIO, RIO) and erector spinae (LES, RES). Electrodes were placed according to Mirka [30], for the rectus abdominis, 3 cm lateral and 2 cm superior to the umbilicus; external oblique 10 cm lateral to the umbilicus with an orientation of 45° to vertical; internal oblique 10 cm lateral to the midline within the lumbar triangle at a 45° orientation; and erector spinae 4 cm lateral to the L3 spinous process. Considering electrode locations, internal oblique activity was representative of extensor and lateral effort whereas external oblique myoactivity was considered flexor and lateral [13,34]. Hair was shaved from the electrode site and the surface abraded with alcohol solution. EMG signals were high-pass filtered at 30 Hz, low-pass filtered at 250 Hz, rectified and integrated using a 5 Hz Hanning low-pass convolution filter. After processing, the signal from each muscle was normalized according to the corresponding peak mean EMG value recorded during maximum isometric flexion, extension, right-lateral twisting and left lateral twisting exertion. In the trials without a sudden load EMG signals from each muscle were averaged over the middle 3 s of the trial. When a sudden load was applied, EMG represented a mean value from 100 ms prior to sudden load impact (Fig. 1). Recognizing the tasks were trunk extension exertions, antagonistic activity was defined as the mean normalized activity from the trunk flexors. To record the influence of fatigue, median power frequency was determined from the raw static EMG data using a power spectral density algorithm (MATLAB, Natick, MA).

Static spinal posture was recorded using surface mounted electromagnetic tracking sensors (Ascension Technology Corp., Burlington, VT). Two sensors were placed over the subject's spinous processes at T10 and S1 and a third marker on the manubrium. Trunk flexion angle was displayed as real-time feedback for the subject to observe. From this display the participants were able to control static trunk flexion angle.

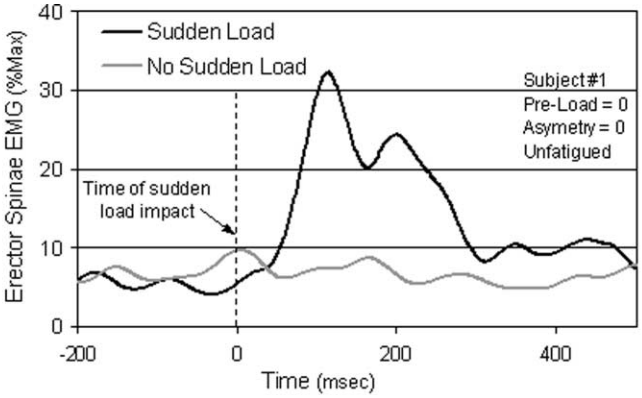


Fig. 1. Typical EMG preparatory and response activity from the erector spinae during sagittally symmetric trials. The black line represents a sudden loading trial and the gray line an equivalent trial with no applied sudden load. The vertical dashed line at time=0 represents the time of the sudden load impact. Note the myoelectric response of the trunk muscles during static extension exertions suggesting the impact was sufficient to warrant a response beginning approx. 55 ms after the impact and peaking 115 ms after impact for this trial. No markedly different preparatory recruitment was observed in the two trials.

2.4. Statistical analysis

Statistical analyses were performed to determine the effects of the lifting parameters on the preparatory EMG. It is recognized that muscle activity and coactivity are markedly influenced by trunk flexion angle, asymmetric posture and static flexion moment [29]. We were specifically interested in the influence of sudden loading condition, fatigue, and gender. Thus, independent mixed-measures MANOVA were performed for the two studies, i.e. flexed and upright postures were analyzed separately. Repeated measures variables included asymmetry, sudden load condition and fatigue while gender served as a between-subjects variable. Analyses were performed using commercial statistical software (Statistica, 4.5, Statsoft, Inc., Tulsa, OK) using a significance level of 0.05 for all tests. Trends in significant variables were investigated using post-hoc analyses with Bonferroni correction.

3. Results

Measured EMG was influenced by pre-load and task asymmetry (Table 1). The kinetic impact was sufficient to disturb the equilibrium of the trunk musculoskeletal system, generating a myoelectric response with similar

Table 1
Mean values representing normalized integrated preparatory EMG values and standard deviations (% MVC) recorded from the 100 ms prior to the sudden load impact and the middle second of the non-sudden-load trials[a]

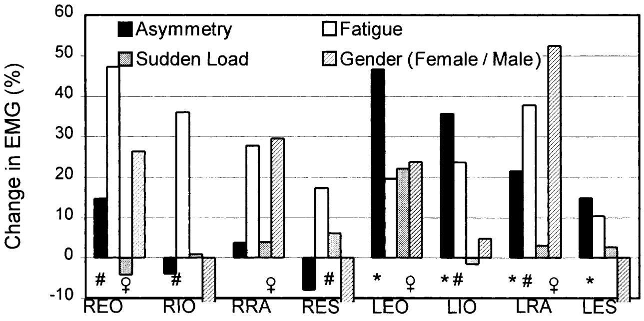
	Muscle							
	REO	RIO	RRA	RES	LEO	LIO	LRA	LES
Gender								
Male	**1.5**±1.1	4.7±3.5	**1.3**±1.3	16.5±11.5	**2.5**±10.6	6.1±4.1	**1.1**±1.1	17.0±10.1
Female	**1.9**±2.1	4.2±3.4	**1.7**±3.0	10.8±6.8	**3.2**±5.1	6.4±5.0	**1.7**±3.0	11.9±7.5
Preload								
0	**1.3**±1.1	**3.2**±3.2	**1.1**±2.3	**10.3**±9.2	**3.4**±6.8	**4.7**±3.9	**1.2**±2.1	**11.4**±8.8
20% MVC	**2.2**±1.1	**5.7**±3.4	**1.8**±2.2	**16.2**±8.5	**4.7**±8.0	**8.2**±5.0	**1.8**±2.3	**17.4**±9.2
Asymmetry								
Symmetric	1.6±0.9	4.6±2.7	1.4±2.0	13.8±6.7	**3.3**±7.2	**5.5**±4.0	**1.4**±1.7	**13.4**±7.3
Left	1.9±1.2	4.4±3.7	1.5±2.5	12.7±10.6	**4.8**±7.7	**7.4**±5.1	**1.7**±2.6	**15.4**±10.6
Fatigue								
Un-fatigued	**1.4**±0.7	**3.8**±2.1	1.3±1.4	**12.2**±5.7	3.7±7.1	**5.8**±3.2	**1.3**±1.6	13.7±6.5
Fatigued	**2.1**±1.3	**5.2**±3.7	1.7±2.8	**14.3**±10.4	4.4±7.8	**7.1**±5.2	**1.8**±2.7	15.2±10.1
Sudden load								
No	1.8±1.2	4.4±3.2	1.4±2.0	12.9±7.5	3.0±3.4	6.5±4.6	1.5±2.0	14.2±8.2
Yes	1.7±0.9	4.5±3.4	1.5±2.5	13.6±10.2	3.6±10.0	6.4±4.7	1.5±2.4	14.6±9.8

[a] Bold indicates statistically significant ANOVA main effect. All values represent EMG in units of %MVC. REO, right external oblique; RIO, right internal oblique; RRA, right rectus abdominis; RES, right erector spinae; LEO, left external oblique; LIO, left internal oblique; LRA, left rectus abdominis; LES, left erector spinae.

characteristics and latency as described in the literature (Fig. 1). Post-hoc analyses demonstrated pre-load weight was associated with a significant increase in preparatory EMG activity for all of the measured trunk muscles, including trunk extensor and antagonistic flexor muscle groups. The asymmetric posture introduced static lateral moments tending to flex the trunk to the right. Consequently, EMG from the all contralateral, i.e. left side muscles, were significantly increased to offset the lateral moment while activity from the right side muscles was not significantly changed. The activity response to preload and task asymmetry behaved as expected and supported the validity of the EMG data in this experiment. Results from the upright posture were similar in all regards and have therefore not been explicitly illustrated.

Gender differences were evident in the coactivation from the flexor muscle groups (Table 1). Normalized EMG coactivity generated by the female subjects was significantly greater than for males in the external obliques and recti abdominis. No significant effects were observed in the extensor muscle groups. In the second study, i.e. in upright postures with no pre-load, female subjects continued to demonstrate significantly increased coactivation. These data may suggest gender differences in recruitment strategies to control trunk stiffness and stability.

Fatigue was associated with increased mean normalized preparatory EMG activity from the trunk muscles (Table 1). Spectral analyses revealed a significant reduction in median power frequency of the right erector spinae. The left erector spinae also demonstrated reduced median frequency, but at a level of $p<0.077$ failed to achieve the a priori value of statistical significance. Thus, results suggest the erector spinae muscles were sufficiently fatigued, with no other muscle group demonstrating fatigue effects. In the fatigued state increased coactivation was observed (Fig. 2). Increased mean integrated magnitude of the EMG signal was recorded from the bilateral internal obliques and the right erector spinae (Table 1). This increased extensor activation was likely recruited to compensate for the fatigue



* Task asymmetry significantly influences the EMG activity
\# Fatigue condition significantly influences the EMG activity
♀ Gender significantly influences the EMG activity

REO = right external oblique
RIO = right internal oblique
RES = right erector spinae
LEO = left external oblique
LIO = left internal oblique
LES = left erector spinae

Fig. 2. Change in preparatory EMG activity of the trunk muscles during static extension exertions. Results represent the mean of both unloaded and 20% MVC lifting exertions including both male and female subjects.

induced loss in force production from the erector spinae groups. Increased activity during the fatigued conditions was also noted in the flexor muscles including the right external obliques and left rectus abdominis. Both of these flexor muscles revealed a significant fatigue-by-gender interaction, with post-hoc analyses demonstrating increased flexor coactivation with fatigue was significant only for the female subjects. Further pair-wise analyses indicated the male subjects demonstrated greater reduction in median power frequency of the erector spinae EMG signal than the females, suggestion potential differences in the level of fatigue, and providing potential insight into the fatigue-by-gender interaction from the integrated EMG signal. It is nonetheless noteworthy that a change in flexor muscle activity was observed when the fatiguing task focused on the extensor musculature.

Statistically significant changes in preparatory activity in anticipation of the sudden load were not observed contrary to the initial hypothesis (Table 1). When subjects were expecting the sudden load, EMG increased by a mean value of 4% relative to the condition of no sudden load, which failed to achieve statistical significance. The mean power frequency of the bilateral rectus abdominis was significantly increased in preparation for the sudden load. However, the amplitude of the rectus abdominis signal was on the order of 2% MVC, thereby prohibiting any valid conclusions from the spectral data of this muscle. Recognizing that intrinsic active muscle stiffness is proportional to the contractile force, in conditions of high pre-loading the equilibrium level of muscle stiffness may be sufficient to maintain stability without need of increased preparatory coactivation. However, even in the low pre-load conditions no increased recruitment activation was noted. To further reduce pre-load the second experiment was performed in the upright posture, thereby eliminating the external flexion moment from the trunk mass. Similar to the flexed posture data, the upright no pre-load conditions did not generate a significant effect for sudden load. In neither condition did expectation of sudden load generate a change in preparatory EMG.

4. Discussion

Biomechanical stability describes the potential of the musculoskeletal system to maintain equilibrium in the presence of kinematic or kinetic disturbances. When the equilibrium posture is in a state of minimum potential energy, the system will return to this minimum energy level if perturbed [37]. One method of achieving this minimum energy state and stability condition is to establish increased stiffness. The stiffness component of active muscle is well recognized and contributes to voluntary control of active joint stiffness and motor control [20]. Hogan [19] observed that antagonistic muscle co-contraction serves to increase the system stiffness of the equivalent joint. Thus, preparatory co-activation can be recruited to stiffen the trunk [6]. Theoretical analyses suggest this coactive stiffening will effectively augment spinal stability [5,11,14]. Without added stiffness from the active muscles, the spine is highly unstable and susceptible to buckling and injury [8,9]. Empirical measurements demonstrate antagonistic coactivation is recruited in response to stability requirements of the trunk [32]. Thus, it was predicted that increased preparatory coactivation would be observed when expecting a sudden loading disturbance. Results from the current study failed to support this hypothesis.

There were no significant changes in muscle activation levels when subjects were expecting a sudden load. Previous studies conclude preparatory strategy may vary markedly from one subject to another [23]. Thomas et al. [36] reported the area under the EMG curves during onset of activity was increased when subjects were permitted to observe the falling mass and predict the timing of the sudden load impact. However, EMG onset rate is slower when subjects are provided with improved timing queues [24]. Whether increased preparatory EMG area was attributable to increased myoactivation or longer duration of onset was not reported. Hodges et al. [17,18] observed increased preparatory activation prior to rapid voluntary trunk loading in superficial muscles opposing the pending trunk moment. The authors conclude that neuromuscular control of superficial muscles does not attempt to stiffen the trunk; rather voluntary "anticipatory postural adjustments involve movements not rigidification of the trunk." Our results agree, noting no statistically significant differences between pre-activation when expecting a sudden load and the equivalent static equilibrium conditions. Conversely, Hodges et al. [17,18] observed increased transverse abdominis activity prior to all applied moment directions and concede the preparatory behavior of this muscle may be recruited to stiffen the trunk. This suggests the superficial muscles measured in the current study respond to the disturbance whereas deep muscles may be recruited in preparation for the perturbation.

Methodological factors may contribute to interpretation of results. The load impulse experienced by our subjects during sudden load conditions resulted from the impact of a 2.5% MVC load falling 0.5 m. This was sufficient to evoke a myoelectric response from the subjects (Fig. 1) but was markedly less threatening than the sudden loads applied in other studies. The magnitude of the load impulse experienced by our subjects was approximately 25% of the impulse applied by Thomas et al. [36] and 35% of the sudden load magnitude applied by Lavender et al. [23]. However, others [21] have concluded pre-activation was not influenced by the magnitude of the expected load impact.

Another methodological difference between the current and previously published studies was the pre-load posture. Previous efforts have examined subjects in upright postures whereas results from the current effort focused primarily on forward and asymmetrically flexed postures at 45°, thereby applying a gravitational moment pre-load to the trunk musculature. Increased pre-load requires greater muscle forces to establish equilibrium. Recognizing that active muscle stiffness is proportional to contractile force [38], it is reasonable that trunk stiffness was greater in conditions of high pre-load [21] and antagonistic coactivation can be reduced while maintaining biomechanical stability in flexed postures [7,14]. It was thought that maybe the magnitude of the sudden load vs the pre-load in the current study failed to exceed the instability threshold, thereby requiring no added coactivation in preparation for the impact. To test this possibility a brief secondary study was performed wherein subjects were exposed to the sudden loading conditions in the upright posture, with no pre-load, and an increased sudden load impact energy, i.e. 5% MVC dropped from 0.5 m. As in the flexed postures, no increase in preparatory activity was observed. Thus, our results agree with others, concluding that the pre-load state may not contribute to preparatory and response behavior.

How was stability maintained in the absence of increased preparatory stiffening? The neuromuscular system can make use of both feed-forward and feedback components to maintain stability. Preparatory stiffening addresses primarily the feed-forward behavior, but no change was observed when stability conditions were modified. This leads us to conclude that the myoelectric response or feedback gain served was the primary stability mechanism in these experimental conditions. Although we have observed elsewhere that coactivation is a significant factor when stability is static in nature [32], the current results indicate dynamic stability relies greatly on neuromuscular feedback. This is supported by others who have proposed that neuromuscular response rate and magnitude may contribute to LBD risk [25,26,28,39]. Further research is necessary to model and quantify the control-feedback stability of the spine.

Epidemiologic studies suggest a link between musculoskeletal fatigue and risk of LBD [2]. Fatigue influences reflex mechanics [1,12,16,27] and has been shown to affect muscle response time in the low-back [39]. If the response mechanism is the primary stability factor in dynamic function, then fatigue must compromise dynamic stability. To compensate for the reduced response stability, coactivation may be recruited to establish increased trunk stiffness. Increased EMG from the extensor muscles following a fatiguing extension exertion was expected as greater motor recruitment is necessary to counteract the loss in muscle force production (Fig. 2). However, it is noteworthy that activity in the flexor muscles following extension fatigue was 33% greater than during the equivalent unfatigued conditions (Table 1). Others have reported similar trends measuring an increase in antagonistic activity following isometric fatiguing exertions [33,35,39]. These results point to potential LBD risk associated with spinal instability from fatigue during MMH tasks. Further research is warranted to fully understand this behavior.

Gender may also play a role in spinal stability. Epidemiologic research indicates females suffer twice the risk of occupationally related musculoskeletal and low-back injuries in MMH tasks [10,22]. Thomas et al. [36] reported no statistically significant gender factors contributing to neuromuscular response following a sudden load whereas Wilder et al. [39] concluded male subjects demonstrated shorter reaction time and duration than women. Empirical measurements indicate increased active and passive stiffness in men vs women [4,15], although there are no data representing the stiffness behavior of the trunk. Thus, to maintain stability females may require increased preparatory coactivity. Gender differences in preparatory coactivation were observed, particularly evident in the external obliques and recti abdominis muscle groups (Table 1). In the upright posture, wherein active muscle stiffness was limited due to reduced pre-load, gender differences were observed in the external obliques, internal obliques, and rectus abdominis. Thus, results support the hypothesis that female subjects in the current study may require increased coactive recruitment to maintain stability. Unfortunately this also increases the potential for fatigue related stability factors. Control of low-back injury may require gender specific preventative measures and more intensive research efforts focusing on gender specific biomechanical factors in musculoskeletal injury.

5. Conclusions

Scientific evidence suggest biomechanical stability of the lumbar spine is an important factor when considering the risk of LBD. Two of the primary components in spinal stability include the preparatory muscle recruitment and the response or feedback behavior. Results from the current study demonstrate no difference in the preparatory coactive muscle recruitment patterns when subjects were waiting in anticipation of a sudden flexion load compared to recruitment patterns observed in similar static posture when the subjects were informed no sudden load would be applied. This indicates greater reliance on the neuromuscular response for the maintenance of stability in dynamic loading conditions. Significant differences in preparatory myoactivity were observed as a function of fatigue and gender suggesting potential risk factors for spinal instability. Results provide insight into the control of spinal stability and identify a need for further research into neuromotor control of biomechanical stability of the spine.

Acknowledgements

We wish to thank S. Wilson, Ph.D. and D. Padua for technical assistance in this effort. This research was supported by grant K01 OH00158-03 from NIOSH of the Centers of Disease Control and Prevention, and grant R01 AR46111-03 from NAIMS of the National Institutes of Health.

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