The Changes of Trunk Motion Rhythm and Spinal Loading During Trunk Flexion and Extension Motions Caused by Lumbar Muscle Fatigue

BOYI HU and XIAOPENG NING

Department of Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV 26506, USA

Associate Editor Thurmon E. Lockhart oversaw the review of this article.

Abstract—Previous studies indicated that lumbar extensor muscle fatigue could potentially affect lumbar–pelvic rhythm and influence spinal loading during trunk motions. In this study, the effects of lumbar extensor muscle fatigue on the normalized lumbar–pelvic rotation rhythm and the associated L5/S1 joint loading during weight lifting and lowering tasks were investigated. Thirteen volunteers performed lifting and lowering of a 20-lbs box both before and after lumbar extensor muscle fatigue, which was generated through a static weight holding task. The normalized lumbar–pelvic motion ratio (L/P ratio) and the external moment on the L5/S1 joint were calculated and compared. Results showed that subjects demonstrated significantly larger normalized L/P ratios during both weight lifting and lowering tasks with the influence of fatigue. In addition, although the spinal loadings remain unchanged at the beginning and ending of both lifting and lowering motions, significantly larger L5/S1 joint moments were observed during both motions after fatigue. Such changes indicate potentially elevated risk of back injury. In a clinical setting, the current results demonstrated that lumbar muscle fatigue could cause transient changes in lumbar–pelvic motion rhythm. Therefore, lumbar muscle fatigue must be avoided when using lumbar–pelvic motion rhythms for patient diagnosis or rehabilitation assessment.

Keywords—Fatigue, Lumbar–pelvic motion ratio, Spinal loading, Low back pain.

INTRODUCTION

Low back pain (LBP) is a significant health problem worldwide.[3] Eighty percent of all individuals will experience LBP at some point in their lives.[47,49] One-third of the adults in the United States will develop some degrees of back pain each year,[2] seven to fifteen percent of the US adults report some daily restriction of activities due to back pain within the previous year, and there are ~700,000 workers' compensation claims for work-related back pain each year.[48] LBP also causes substantial economic burden each year around the world.[31] In the United States, it was estimated that annual cost was close to 20 billion dollars.[44]

The exact etiology of LBP is still unclear,[20,22,37] however, previous studies have identified a number of risk factors that are associated with the occurrence of LBP, such as high spinal compression[10,11] and shear loading,[25,26] uneven ground condition[14,15,19,35] and lumbar tissue creep.[39,40] Previous studies also demonstrated that lumbar extensor muscle fatigue could reduce trunk and spinal stability[4,13] and alter the neuromuscular coordination for lumbar tissues during trunk bending;[6] however, the direct association between lumbar extensor muscle fatigue and LBP is still not well understood. Previously, studies have found that lumbar extensor muscle fatigue alters the onset and cessation of myoelectric silence during the performance of flexion–extension tasks;[6] such change indicated a shift of loading from active muscles to lumbar passive tissues. From the spinal stability point of view, one study demonstrated that lumbar extensor muscle fatigue increased body sway during standing possibly due to decreased muscle proprioceptive acuity, impaired postural control and reduced trunk stability.[4] Another study discovered elevated trunk muscle co-contraction after lumbar muscle fatigue.[13] It was concluded that the increase of muscle co-contraction was used to compensate for the reduced stability and to increase trunk stiffness. A following study showed that lumbar extensor fatigue led to reduced spinal dynamic stability and reduced dynamic complexity during sagittal flexion and extension motion[9] which could increase the chance of uncontrollable

Address correspondence to Xiaopeng Ning, Department of Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV 26506, USA. Electronic mails: bohu@mix.wvu.edu and xiaopeng.ning@mail.wvu.edu

intervertebral disk movement and tissue injury when experience perturbation.

Lumbar extensor muscle fatigue could also change lifting kinematics. Previous studies have documented that lumbar extensor muscle fatigue introduced by repetitive lifting could reduce trunk stability and cause reduced knee and hip range of motion and increased peak lumbar flexion angle during lifting.[42,43] Understanding trunk kinematics is essential for the assessment of LBP risks. Especially in flexed postures, trunk motion to a large extent determines the magnitude of spinal loading[18,29,46]) which is directly associated with the occurrence of LBP.[23,24,27] A recent study found that changes in the motion synergy between different trunk motion segments (e.g., lumbar, pelvis) during lifting could also significantly influence the spinal loading.[45] However, the effect of lumbar extensor muscle fatigue on trunk motion synergy during the performance of trunk flexion and extension tasks has not been investigated.

Previous studies have demonstrated that LBP patients generate different lumbar pelvic motion rhythms in comparison to non-symptomatic individuals.[38,41] In clinical settings such difference could be used for patient screening and monitoring the rehabilitation progress of patients. Understanding the effect of lumbar muscle fatigue on the lumbar pelvic motion rhythm could help physicians improve the accuracy of diagnostic and rehabilitation assessment of LBP patients.

The objective of this current study was to understand the effect of lumbar extensor muscle fatigue on lumbar–pelvic motion rhythm during weight lifting and lowering motions. More specifically, we investigated the effect of lumbar extensor muscle fatigue on normalized lumbar–pelvic rotation ratio and the corresponding L5/S1 joint loading. Based on the existing evidence,[45] it was hypothesized that, with the influence of lumbar extensor muscle fatigue, non-symptomatic subjects will demonstrate increased normalized lumbar–pelvic rotation ratio and elevated spinal loading during trunk flexion and extension motion.

METHODS

Participants

Thirteen male subjects participated in this study with signed consent form. Their mean age, height, BMI and mass were 27.0 ± 2.5 years, 175.2 ± 5.0 cm, 22.3 ± 2.3, and 68.8 ± 9.8 kg, respectively. The experiment protocol received approval from the West Virginia University Institutional Review Board. Subjects with a history of low back surgery or experienced lower back pain within the past 12 months were excluded from the current study.

Instrumentation

A three-dimensional, magnetic field based motion tracking system (Motion Star, Ascension Technology Corporation, Burlington, VT, USA) was used to measure lumbar and pelvis kinematics in this experiment. Three motion sensors were attached to the skin over the spinous processes at C7, T12, and S1 levels respectively (Fig. 1a). Muscle electromyography (EMG) data were collected from the left and right side of paraspinal muscles from L3 (4 cm lateral from the L3 spinous process) and L4 levels (2 cm lateral from the L4 spinous process) using bipolar surface EMG electrodes (Bagnoli, Delsys, Boston, MA, USA) (Fig. 1a). The MotionMonitor software (Motion-Monitor, Innovative Sports Training, Chicago, IL, USA) was used to collect kinematics and EMG data simultaneously with a sampling frequency of 1024 Hz. A custom made wood structure was used to standardize subject's posture and reduce stress and strain on lower extremity muscles and ligaments during the performance of lumbar extensor muscle fatiguing tasks. This structure is the combination of a standing platform and an attached leg support. A nylon safety belt was used to secure subject's pelvis to the leg support in order to minimize lower extremity motions.

Independent and Dependent Variables

In the current experiment, a single independent variable: lumbar extensor muscle fatigue (with or without) was investigated. A fatiguing protocol was adopted to generate low back extensor muscle fatigue (detailed in the 'Protocol' section) and the median frequencies of the erector spinae EMG signals were used to quantify the accumulation of muscle fatigue. Four dependent variables were involved: (1) maximum lumbar rotation angle, lumbar rotation angle was defined as the angular difference between the T12 and S1 motion sensors in the sagittal plane (Fig. 1b); (2) maximum pelvis rotation angle; pelvis rotation angle was defined as the relative rotation of S1 sensor from the upright posture in the sagittal plane (Fig. 1b); (3). normalized lumbar–pelvic rotation ratios during both trunk flexion and extension motions. For each trail, lumbar and pelvis motions were normalized to their own range of motion (i.e., 0% motion at upright standing posture and 100% motion at trunk full flexion posture) respectively. Detailed description of this normalization process is included in the 'Data processing' section; 4. moment on the L5/S1 joint.
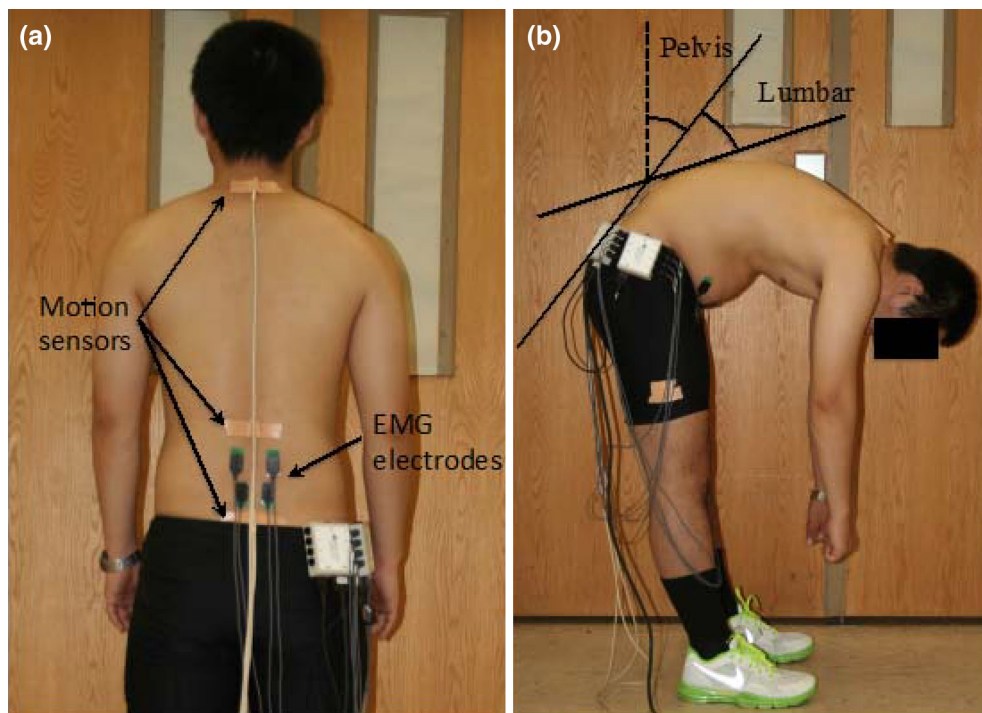
FIGURE 1. Demonstration of experiment setup and the calculation of pelvis and lumbar rotation angles.

Protocol

Upon arrival, subjects first signed an informed consent form, then a 5-min warm-up session was provided to allow subjects to stretch and warm up muscles. Next, the skin over the sampling locations was shaved and swabbed using alcohol and cotton pad. The motion sensors and EMG electrodes were then placed using double-sided tape following previous instructions.[14,33] When data collection started, subjects first conducted five repetitions of sagittally symmetric weight lifting and lowering tasks using a 20-lbs box placed 40 cm from the center of ankles (Fig. 2a). The number of repetitions was chosen to both provide enough statistical power and to avoid unwanted muscle fatigue before the fatiguing protocol. Subjects were required to use stoop lifting technique with both arms maintained straight and move at their natural pace without abrupt changes in motion. At least 1-min rests were provided between each two repetitions. When finished, subjects moved to the custom made structure to conduct the fatiguing protocol with pelvis fully secured (Fig. 2b). The fatiguing protocol requires subjects to maintain a ~45 degree trunk flexion posture with back kept straight while holding the same 20-lbs box until exhausted. After the fatiguing protocol, another five repetitions of box lifting and lowering tasks were conducted without rest in between in order to avoid significant recovery of lumbar muscle fatigue. Additionally, fatigue measurement tasks were also

performed four times during the data collection: (1) at the beginning of the data collection; (2) immediately after the first five repetitions of box lifting and lowering tasks; (3) immediately after the fatigue protocol; (4) immediately after the second five repetitions of box lifting and lowering tasks. The fatigue measurement task requires subjects to hold the 20-lbs box and maintain a ~45 degree trunk flexion posture for 6 s, with pelvis secured by the custom made apparatus. The median frequencies of erector spinae EMG signals from the fatigue measurement tasks were used to verify (1) activities prior to the fatiguing protocol did not generate significant muscle fatigue; (2) significant muscle fatigue was generated during the fatiguing protocol and (3) Muscle fatigue remained until the end of the data collection.

Data Processing

The pelvis and lumbar rotation data were normalized from 0 (i.e. upright posture) to 1 (i.e. full flexion posture) with respect to their range of motion. The lifting and lowering motions were both divided into 10 sub-segments based on the normalized pelvis rotational angle and the normalized lumbar rotational angles at 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th percentile of normalized pelvis rotational angle were compared. The dynamic external moment that imposed on the L5/S1 joint was estimated using a
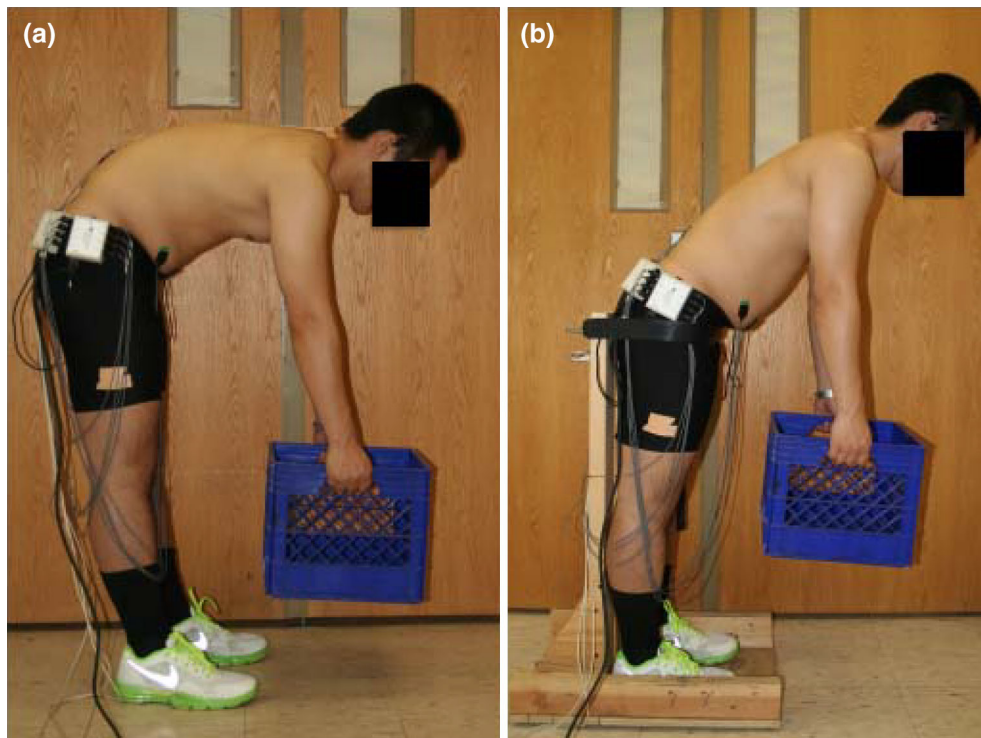
FIGURE 2. (a) A snapshot that demonstrates the weight lifting and lowering task and (b) Subject secured in the custom-made structure and perform the fatiguing protocol.

previously developed physical model[16,17,34] which considers trunk flexion angle, instantaneous linear and angular accelerations; the upper body mass and center of mass were estimated based on subjects' anthropometric measurements (body height, weight, trunk length, trunk width, etc.,) as well as trunk kinematic data.[30]

A custom Matlab (Matlab 2010, MathWorks, USA) program was developed to process the EMG and kinematics data. The EMG signals were first transferred into frequency domain using Fast Fourier Transformation (FFT) and then passed through a notch filter at 60 Hz and its aliases, a 500 Hz low-pass filter and a 10 Hz high-pass filter. The median frequencies of the EMG data collected during the fatigue measurement tasks were calculated using method described in the previous literature.[21]

Statistical Analysis

The effects of lumbar extensor muscle fatigue on all dependent variables were tested using paired t test in order to reduce the between-subject variance. Each repetition was treated as a single observation and was used for the paired difference analysis with subject being the blocking variable. Minitab (Minitab 15, Minitab Inc., State College, PA, USA) was used for statistical analyzes with significance level of $p < 0.05$.

RESULTS

Extensor Muscle Fatigue

The lumbar extensor muscle fatigue was characterized by the decrease of EMG median frequency.[21] Data from the fatigue measurement tasks demonstrated that no statistically significant lumbar extensor muscle fatigue was introduced after conducting the five repetitions of weight lifting tasks (average median frequency changes from 62.77 (3.53) Hz to 60.29 (2.45) Hz, p value = 0.56). On the other hand, the fatiguing protocol successfully generated lumbar extensor muscle fatigue, which is demonstrated by the significant reduction of EMG median frequency after the fatiguing protocol (average median frequency changes from 60.29 (2.45) Hz to 52.70 (1.37) Hz, p value = 0.004). Finally, no clear recovery of muscle fatigue after the second five repetitions of weight lifting and lowering tasks was observed (average median frequency changes from 52.70 (1.37) Hz to 52.63 (1.49) Hz, p value = 1.00). Collectively, these results showed that the goal of our experiment design was successfully achieved.

Lumbar and Pelvis Maximum Rotation

Results of the statistical analysis showed that during the performance of weight lifting tasks neither the
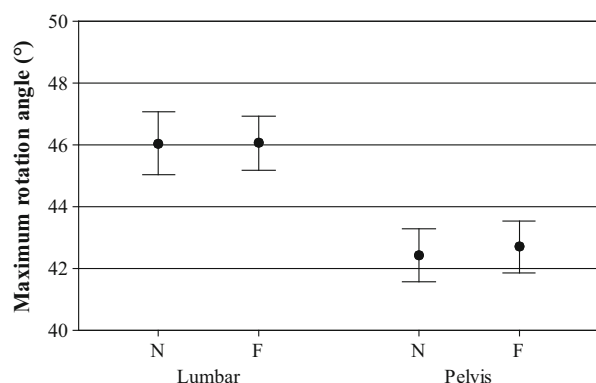
FIGURE 3. The maximum lumbar and pelvis rotation angles in normal (N) and fatigued (F) conditions. Bars indicate the corresponding standard error.
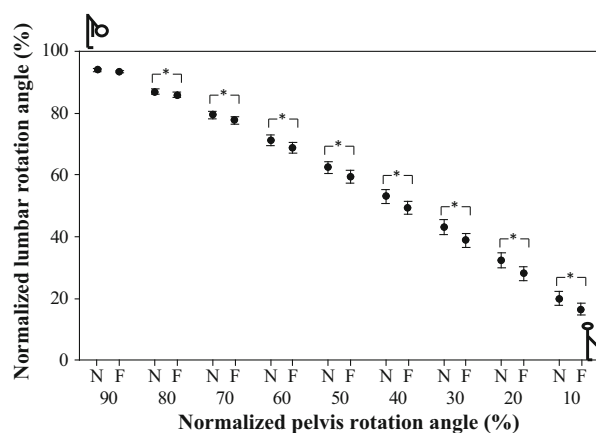

FIGURE 5. The comparison of normalized lumbar–pelvic coordination during lowering motion between normal (N) and fatigue (F) conditions. Asterisk marks represent that the two conditions are statistically different from each other and bars indicate the corresponding standard error.

FIGURE 4. The comparison of normalized lumbar–pelvic coordination during lifting motion between normal (N) and fatigue (F) conditions. Asterisk marks represent that the two conditions are statistically different from each other and bars indicate the corresponding standard error.

FIGURE 6. The comparison of L5/S1 external moment during weight lifting task between normal (N) and fatigue (F) conditions. Asterisk marks represent that the two conditions are statistically different from each other and bars indicate the corresponding standard error.

maximum lumbar rotation angle (p value = 0.973) nor the maximum pelvis rotation angle (p value = 0.620) was significantly affected by muscle fatigue (Fig. 3).

Normalized Lumbar–Pelvis Ratio

Lumbar extensor muscle fatigue significantly influenced normalized lumbar–pelvic coordination during weight lifting and lowering tasks (Figs. 4 and 5 respectively). It can be observed from Fig. 4 that during lifting motions, at a given percentage of pelvis rotation, subjects had larger lumbar rotation (note that the initial posture is at 100% of lumbar flexion) with the influence of lumbar muscle fatigue (except at the 90th percentile of normalized pelvis rotation). Similarly, during the weight lowering motion larger lumbar rotations were observed (except at the 10th, 20th, and 30th percentile of normalized pelvis rotation) as shown in Fig. 5.
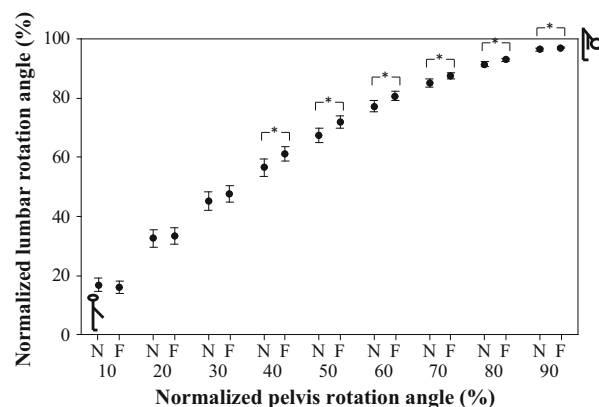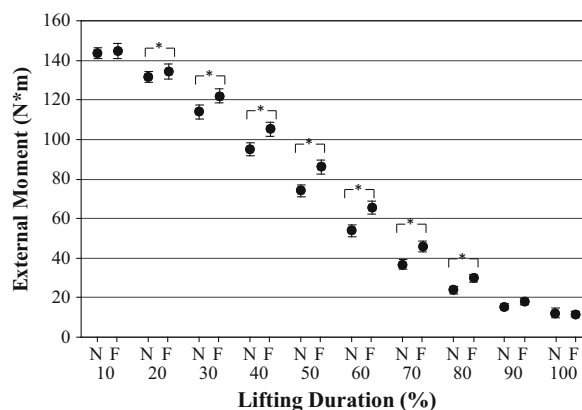
Spinal Loading

To demonstrate the effect of lumbar extensor muscle fatigue on spinal loading during weight lifting and lowering motions. The L5/S1 joint moments during both lifting and lowering motions were calculated from 10th to 100th percentiles of lifting/lowering duration. Results of our analyzes showed that with the influence of lumbar extensor muscle fatigue subjects experienced significantly larger L5/S1 joint moment during both weight lifting and lowering motions (Figs. 6 and 7).

DISCUSSIONS

The purpose of the current study was to quantify the influence of lumbar extensor muscle fatigue on the changes of lumbar and pelvis motion synergy during
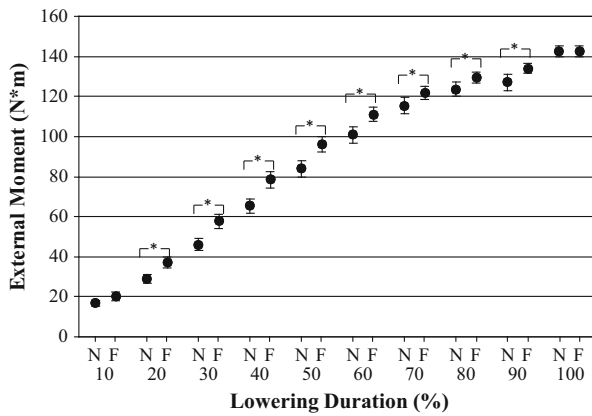
FIGURE 7. The comparison of L5/S1 external moments during weight lowering task between normal (N) and fatigue (F) conditions. Asterisk marks represent that the two conditions are statistically different from each other and bars indicate the corresponding standard error.

weight lifting and lowering tasks. Results of the current study showed that after lumbar muscle became fatigued subjects adopted larger lumbar–pelvic motion ratio during both weighting lifting and lowering, such changes in kinematics also resulted in larger spinal loading. These results supported our initial hypotheses.

Early studies suggested that spinal motion is achieved by the sequential contribution of both pelvis and lumbar segments.[5,8] More specifically, the beginning phase of trunk extension motion is initiated by pelvis moment while the ending phase (i.e. close to upright posture) is achieved mainly by lumbar spine extension motion. It was also believed that the trunk flexion motion is just the inverse process of the extension motion.[8] On the other hand, more recent studies concluded that pelvis and lumbar motion occurred simultaneously during trunk flexion and extension motion.[7,12,32,36,45] Results of the current study demonstrated that despite differ in magnitude, both lumbar and pelvis segments moved simultaneously during weight lifting and lowering tasks, which agreed with findings in the recent literature. In addition, the current results also showed that after fatigue, the lumbar and pelvis motions remain simultaneous even though the lumbar–pelvic ratio was significantly increased.

To further validate the results of the current study, we compared the lumbar–pelvic (L/P) ratios observed in the current study with values reported from previous studies. To be consistent with previous literature, trunk motions during weight lifting and lowering were equally (based on trunk angle) divided into four intervals (0–25, 25–50, 50–75 and 75–100% of maximum trunk angle), for a lowering motion, 0% represents the upright stand posture while for a lifting
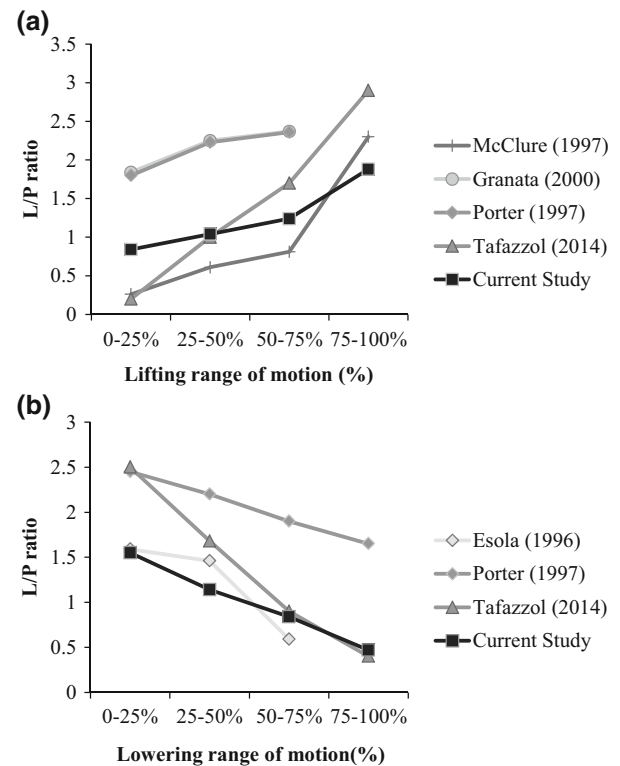

FIGURE 8. The comparison of L/P ratios recorded in the current study with previous literature: a weight lifting motion; b weight lowering motion. During the lowering motion, 0% represents the upright stand posture while during the lifting motion 0% represents the flexed trunk posture that subject initiate the lift.

motion 0% represents the flexed trunk posture where subject initiates the lift. The L/P ratios were calculated in each interval by dividing the changes of lumbar rotation by the changes of pelvis rotation.[7,28,45] Based on the results of the current study, without the influence of muscle fatigue, during weight lifting motion, the L/P ratio increased from 0.84 in first quarter (0–25%) to 1.88 in the fourth quarter (75–100%) of trunk range of motion (ROM) (Fig. 8a). On the other hand, during weight lowering motion the L/P ratio decreased from 1.55 in the first quarter (0–25%) to 0.47 in fourth quarter (75–100%) of trunk ROM (Fig. 8b), such changes in general agreed with data reported in previous studies.[7,12,28,45]

The results of the current study indicated that with the influence of lumbar extensor muscle fatigue subjects adopted higher L/P ratio during both weight lifting and weight lowering motions. Previous study reported that lumbar extensor muscle fatigue causes the cessation of EMG activities occur earlier on these muscles during trunk flexion and extension motions.[6] It means that lumbar muscles are activated in a smaller range of trunk motion, in turn, lumbar

passive tissues including ligaments, tendons and the elastic component of lumbar muscles need to compensate for the lost of active muscle force.[34] In other words, the lumbar passive tissues were further elongated to exert larger elastic forces in order to counterbalance the external loading. Because the strain on lumbar posterior tissue is highly determined by the magnitude of lumbar flexion,[29] therefore larger lumbar and pelvis rotation ratios were observed during trunk motions.

Such transition of loading, from lumbar active muscles to passive tissues would also influence the spinal loading. The structure of lumbar spine determines that lumbar posterior ligaments have shorter moment arm to the center of the L5/S1 joint compare to lumbar extensor muscles, therefore, to counterbalance the same amount of external loading, the increase of loading on lumbar passive tissues could potentially result in higher spinal compression and shear forces on intervertebral disks.[1] Such effect combined with the observed increase in spinal external loading (Figs. 6 and 7) could further elevate spinal compressive and shear loading which may increase the risk of LBP.[10,11,25,26]

Several limitations of the current study need to be noted. First, in the current experiment design, a single level of hand load was used, the potential interaction effect between hand load and muscle fatigue on lumbar–pelvic motion ratio was not explored. Second, only stoop lifting was tested in the current study. Lumbar muscle fatigue may have different influences on other lifting techniques therefore warrants further investigation. Finally, with only male subjects included in the current study, the influence of gender was not tested.

CONCLUSION

Lumbar muscle fatigue alters lumbar–pelvic motion ratio during the performance of both weight lifting and lowering tasks. Such change elevates spinal moment, which may lead to higher spinal compressive and shear loadings and the associated risk of LBP. Results of this study further confirmed lumbar muscle fatigue as an injury risk factor during the performance of material handling especially lifting tasks. In a clinical setting, the current results indicate that subjects experiencing lumbar muscle fatigue may demonstrate transient changes of lumbar–pelvic motion rhythm that similar to that observed among LBP patients.[7,28] Therefore, lumbar muscle fatigue must be avoided when using lumbar–pelvic motion rhythms for patient diagnosis or rehabilitation assessment.

REFERENCES

[1]Bogduk, N. A reappraisal of the anatomy of the human lumbar erector spinae. *J. Anat.* 131:525–540, 1980.
[2]Bureau of Labor Statistics. Nonfatal occupational injuries and illnesses requiring days away from work [online], 2011. Available from: www.bls.gov/iif/oshcdnew.htm.
[3]Dagenais, S., J. Caro, and S. Haldeman. A systematic review of low back pain cost of illness studies in the United States and internationally. *Spine J.* 8:8–20, 2008.
[4]Davidson, B. S., M. L. Madigan, and M. A. Nussbaum. Effects of lumbar extensor fatigue and fatigue rate on postural sway. *Eur. J. Appl. Physiol.* 93:183–189, 2004.
[5]Davis, P. R., J. D. Troup, and J. H. Burnard. Movements of the thoracic and lumbar spine when lifting: a chrono-cyclophotographic study. *J. Anat.* 99:13–26, 1965.
[6]Descarreaux, M., D. Lafond, R. J. Gauthier, H. Centomo, V. Cantin. Changes in the flexion relaxation response induce d by lumbar muscle fatigue. *BMC Musculoskelet Disord.*:9–10, 2008.
[7]Esola, M. A., P. W. McClure, G. K. Fitzgerald, and S. Siegler. Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine* 21:71–78, 1996.
[8]Farfan, H. F. Muscular mechanism of the lumbar spine and the position of power and efficiency. *Orthop. Clin. North Am.* 6:135–144, 1975.
[9]Granata, K. P., and P. Gottipati. Fatigue influences the dynamics stability of the torso. *Ergonomics* 51:1258–1271, 2008.
[10]Granata, K. P., and W. S. Marras. An EMG-assisted model of loads on the lumbar spine during asymmetric trunk extensions. *J. Biomech.* 26:1429–1438, 1993.
[11]Granata, K. P., W. S. Marras, and K. G. Davis. Biomechanical assessment of lifting dynamics, muscle activity and spinal loads while using three different styles of lifting belt. *Clin. Biomech.* 12:107–115, 1997.
[12]Granata, K. P., and A. H. Sanford. Lumbar–pelvic coordination is influenced by lifting task parameters. *Spine* 25:1413–1418, 2000.
[13]Granata, K. P., G. P. Slota, and S. E. Wilson. Influence of fatigue in neuromuscular control of spinal stability. *Hum. Factors* 46:81–91, 2004.
[14]Hu, B., X. Ning, and A. D. Nimbarte. The changes of lumbar muscle flexion-relaxation response due to laterally slanted ground surfaces. *Ergonomics* 56:1295–1303, 2013.
[15]Hu, B., X. Ning, and A. D. Nimbarte. Changes of lumbar muscle flexion relaxation phenomenon when standing on unilaterally elevated ground. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 57:925–928, 2013.
[16]Hu, B., X. Ning, and M. A. Nussbaum. The influence of hand load on lumbar–pelvic coordination during lifting task. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 58:1617–1621, 2014.
[17]Hu, B., X. Shan, J. Zhou, and X. Ning. The effects of stance width and foot posture on lumbar muscle flexion relaxation phenomenon. *Clin. Biomech.* 29:311–316, 2014.

[18]Jia, B., S. Kim, and M. A. Nussbaum. An EMG-based model to estimate lumbar muscle forces and spinal loads during complex, high-effort tasks: Development and application to residential construction using prefabricated walls. *Int. J. Ind. Ergon.* 41:437–446, 2011.

[19]Jiang, Z., G. Shin, J. Freeman, S. Reid, and G. A. Mirka. A study of lifting tasks performed on laterally slanted ground surfaces. *Ergonomics* 48(7):782–795, 2005.

[20]Kankaanpaa, M., S. Taimela, D. Laaksonen, O. Hanninen, and O. Airaksinen. Back and hip extensor fatigability in chronic low back pain patients and controls. *Arch. Phys. Med. Rehabil.* 79:412–417, 1998.

[21]Luca, De. The use of surface electromyography in biomechanics. *J. Appl. Biomech.* 13:135–163, 1997.

[22]Luoto, S., H. Heliovaara, H. Hurri, and H. Alaranta. Static back endurance and the risk of low-back pain. *Clin. Biomech.* 10:323–324, 1995.

[23]Marras, W. S., S. A. Ferguson, D. Burr, and K. G. Davis. Functional impairment as a predictor of spine loading. *Spine* 30:729–737, 2005.

[24]Marras, W. S., S. A. Ferguson, S. A. Lavender, R. E. Splittstoesser, and G. Yang. Cumulative spine loading and clinically meaningful declines in low back function. *Hum. Factors* 56:29–43, 2014.

[25]Marras, W. S., and K. P. Granata. A biomechanical assessment and model of axial twisting in the thoracolumbar spine. *Spine* 20:1440–1451, 1995.

[26]Marras, W. S., and K. P. Granata. An EMG-assisted model of trunk later bending. *J. Biomech.* 30:697–703, 1997.

[27]Marras, W. S., G. G. Knapik, and S. A. Ferguson. Loading along the lumbar spine as influenced by speed, control, load magnitude, and handle height during pushing. *Clin. Biomech.* 24:155–163, 2009.

[28]McClure, P. W., M. Esola, R. Schreier, and S. Siegler. Kinematic analysis of lumbar and hip motion while rising from a forward, flexed position in patients with and without a history of low back pain. *Spine* 22:552–558, 1997.

[29]McGill, S. M., and R. W. Norman. Partitioning of the L4-L5 dynamic moment into disc, ligamentous, and muscular components during lifting. *Spine* 11:666–678, 1986.

[30]Mirka, G. A., A. Baker, A. Harrison, and D. Kelaher. The interaction between load and coupling during dynamic manual materials handling tasks. *Occup. Ergon.* 1:3–11, 1998.

[31]Muslim, K., B. Bazrgari, B. Hendershot, N. Toosizadeh, M. Nussbaum, and M. L. Madigan. Disturbance and recovery of trunk mechanical and neuromuscular behaviors following repeated static trunk flexion: influences of duration and duty cycle on creep-induced effects. *Appl. Ergon.* 44:643–651, 2013.

[32]Nelson, J. M., R. P. Walmsley, and J. M. Stevenson. Relative lumbar and pelvic motion during loaded spinal flexion/extension. *Spine* 20:199–204, 1995.

[33]Ning, X., S. Jin, O. Haddad, and G. A. Mirka. Influence of asymmetry on the flexion relaxation response of the low back musculature. *Clin. Biomech.* 26:35–39, 2011.

[34]Ning, X., S. Jin, and G. A. Mirka. Describing the active region boundary of EMG-assisted biomechanical models of the low back. *Clin. Biomech.* 27:422–427, 2012.

[35]Ning, X., and G. A. Mirka. The effect of sinusoidal rolling ground motion on lifting biomechanics. *Appl. Ergon.* 42(1):131–137, 2010.

[36]Paquet, N., F. Malouin, and C. L. Richards. Hip-Spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine* 19:596–603, 1994.

[37]Roy, S. H., C. J. De Luca, L. Snyder-Mackler, M. S. Emley, R. L. Crenshaw, and J. P. Lyons. Fatigue, recovery, and low back pain in varsity rowers. *Med. Sci. Sports Exerc.* 22:463–469, 1990.

[38]Seay, J. F., R. E. A. Van Emmerik, and J. Hamill. Low back pain status affects pelvis-trunk coordination and variability during walking and running. *Clin. Biomech.* 26:572–578, 2011.

[39]Shin, G., C. D'Souza, and Y. Liu. Creep and fatigue development in the low back in static flexion. *Spine* 34:1873–1878, 2009.

[40]Shin, G., and G. A. Mirka. An in vivo assessment of the low back response to prolonged flexion: Interplay between active and passive tissues. *Clin. Biomech.* 22:965–971, 2007.

[41]Shum, G. L. K., J. Crosbie, and R. Y. W. Lee. Effect of low back pain on the kinematics and joint coordination of the lumbar spine and hip during sit-to-stand and stand-to-sit. *Spine* 30:1998–2004, 2005.

[42]Sparto, P. J., M. Parnianpour, T. E. Reinsel, and S. Simon. The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *J. Orthop. Sports Phys. Ther.* 25:3–12, 1997.

[43]Sparto, P. J., M. Parnianpour, T. E. Reinsel, and S. Simon. (2). ***The effect of fatigue on multijoint kinematics and load sharing during a repetitive lifting test. *Spine* 22:2647–2654, 1997.

[44]Stewart, W. F., J. A. Ricci, D. Morganstein, and R. Lipton. Lost productive time and cost due to common pain conditions in the US workforce. *J. Am. Med. Assoc.* 290:2443–2454, 2003.

[45]Tafazzol, A., N. Arjmand, A. Shirazi-Adl, and M. Parnianpour. Lumbopelvic rhythm during forward and backward sagittal trunk rotations: Combined in vivo measurement with inertial tracking device and biomechanical modeling. *Clin. Biomech.* 29(1):7–13, 2014.

[46]Toosizadeh, N., M. A. Nussbaum, B. Bazrgari, and M. L. Madigan. Load-relaxation properties of the human trunk in response to prolonged flexion: measuring and modeling the effect of flexion angle. *PloS one* 7:e48625, 2012.

[47]Van Tulder, M. W., B. W. Koes, and L. M. Bouter. A cost-of-illness study of back pain in The Netherlands. *Pain* 62:233–240, 1995.

[48]Waddell, G. The back pain revolution. Edinburgh, New York: Churchill Livingstone, 2004.

[49]Wong, T. K. T., and R. Y. W. Lee. Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Hum. Mov. Sci.* 23:21–34, 2004.