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The influence of lumbar extensor muscle fatigue on lumbar–pelvic coordination during weightlifting

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Lumbar muscle fatigue is a potential risk factor for the development of low back pain. In this study, we investigated the influence of lumbar extensor muscle fatigue on lumbar–pelvic coordination patterns during weightlifting. Each of the 15 male subjects performed five repetitions of weightlifting tasks both before and after a lumbar extensor muscle fatiguing protocol. Lumbar muscle electromyography was collected to assess fatigue. Trunk kinematics was recorded to calculate lumbar–pelvic continuous relative phase (CRP) and CRP variability. Results showed that fatigue significantly reduced the average lumbar–pelvic CRP value (from 0.33 to 0.29 rad) during weightlifting. The average CRP variability reduced from 0.17 to 0.15 rad, yet this change ws statistically not significant. Further analyses also discovered elevated spinal loading during weightlifting after the development of lumbar extensor muscle fatigue. Our results suggest that frequently experienced lumbar extensor muscle fatigue should be avoided in an occupational environment.

Practitioner Summary: Lumbar extensor muscle fatigue generates more in-phase lumbar–pelvic coordination patterns and elevated spinal loading during lifting. Such increase in spinal loading may indicate higher risk of back injury. Our results suggest that frequently experienced lumbar muscle fatigue should be avoided to reduce the risk of LBP.

Keywords: lumbar extensor muscle fatigue; lumbar–pelvic coordination; continuous relative phase; low back pain

1. Introduction

Low back pain (LBP) remains the most prevalent musculoskeletal disorder worldwide (Baldwin 2004; Manchikanti et al. 2009; Muslim et al. 2013). In the USA, it was estimated that 80% of the population would experience LBP at least once in their lifetime (Maetzel and Li 2002). LBP patients often suffer from trauma and immobilisation (Fritz and George 2000) which generate tremendous economic costs. Previous studies indicated that LBP is responsible for more than 90 billion dollars of annual medical expenses (Luo et al. 2003).

Low back muscle fatigue has long been identified as a potential risk factor for the development of LBP (Biering-Sorenson 1984; Luoto et al. 1995; Kankaanpää et al. 1998; Roy et al. 1990). One study showed that lumbar extensor muscle fatigue could alter the load-sharing mechanism between lumbar muscles and ligaments during the performance of trunk flexion and extension tasks (Descarreaux et al. 2008). Such change could potentially alter the intervertebral disc loading which is highly associated with the occurrence of LBP (Rodrigo, Goonetilleke, and Xiong 2013; Marras et al. 2005). Other studies investigated the relationship between fatigue and muscle reflex performance (Moore et al. 2002). Particularly, one study discovered significantly increased trunk muscle reflex time in reaction to external sudden loading events with the influence of muscle fatigue (Wilder et al. 1996). This delay in muscle reflex could reduce lumbar stability, and increase trunk kinematic responses to external impact, thereby elevating the risk of LBP. Although previous studies have illustrated the potential mechanisms that lumbar muscle fatigue contributes to the occurrence of LBP, however, direct evidences that link lumbar muscle fatigue to LBP symptoms are still lacking.

LBP patients demonstrated different motion patterns compared to non-symptomatic population (Hamill, Haddad, and Mcdermott 2000). One study compared the difference of pelvis–trunk coordination and variability between LBP patients and non-symptomatic subjects during walking and running (Seay, Van Emmerik, and Hamill 2011). Results of this study showed that in both tasks, LBP patients demonstrated more in-phase pelvis–trunk coordination in the frontal plane and reduced coordination variability in the transverse plane. Another study investigated the lumbar–pelvic coordination during sit-to-stand and stand-to-sit motions among healthy subjects and patients with LBP (Shum, Crosbie, and Lee 2005). The authors observed less lumbar motion and more pelvic motion among LBP patients in comparison to healthy subjects, and such change could influence spinal loading (Tafazzol et al. 2014), which is directly associated with the risk of LBP (Norman et al. 1998; Bakker et al. 2007).

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The purpose of this study was to better understand the influence of lumbar extensor muscle fatigue on lifting kinematics and the associated LBP risks. More specifically, we investigated how the magnitude of lumbar extensor fatigue could change the lumbar-pelvic motion coordination during lifting tasks among non-symptomatic subjects. The spinal loadings during lifting tasks were also compared before and after lumbar extensor muscle fatigue. Based on the existing evidence, it was hypothesised that subjects may demonstrate more in-phase lumbar–pelvic coordination and reduced lumbar–pelvic motion variability during lifting after the influence of lumbar muscle fatigue. In addition, we suspected that changes in motion coordination might increase spinal loading during lifting tasks after muscle fatigue.

2. Materials and methods

2.1 Participants

Fifteen male volunteers (average age 25.8 ± 2.7 years, body mass 76.6 ± 7.5 kg, body height 1.73 ± 5.5 cm) participated in this study. Individuals with a history of LBP within the past 18 months that required medical attention were excluded from the study population. The experiment design and procedures were approved by the Institutional Review Board of West Virginia University.

2.2 Instrumentation

Lumbar and pelvic kinematics were collected using a magnetic field-based motion tracking system (Motion Star, Ascension, Burlington, VT, USA) with two magnetic sensors secured to the skin surface of the T12 and S1 spinous processes. The pelvis rotation angle was obtained as the relative rotation of S1 sensor in the sagittal plane. The lumbar flexion angle was defined as the angular difference between T12 and S1 motion sensors in the sagittal plane (Figure 1(a)). Muscle electromyography (EMG) was sampled using bipolar surface EMG electrodes (Bagnoli, Delsys, Boston, MA, USA) placed over the skin of the left and right erector spine muscles (4 cm lateral to the L3 spinous process) (Ning et al. 2011; Hu, Ning, and Nimbarte 2013a, 2013b). EMG and kinematics data were both sampled at 1024 Hz and synchronised using the MotionMonitor software (MotionMonitor, Innovative Sports Training, Chicago, IL, USA). A custom-made pelvis restriction apparatus was used in the fatiguing protocol to help maintain lumbar and trunk postures and reduce strain and discomfort among leg muscles (Figure 1(b)) (Ning 2011).

2.3 Independent and dependent variables

The lumbar extensor muscle fatigue (with or without) was the only independent variable involved in this study. Three dependent variables were investigated: (1) lumbar–pelvic Continuous Relative Phase (CRP). The CRP was calculated as the difference in phase plane angles between lumbar and pelvis during a movement; CRP is critical in deciphering the motion synergy of multiple segments during task performance (Scholz 1990; Schöner, Jiang, and Kelso 1990). (2) Lumbar–pelvic CRP variability. CRP variability was defined as the standard deviation of the CRP for each task. Detailed computational procedure can be found in the *Data processing* session. (3) External moment on the L5/S1 joint.

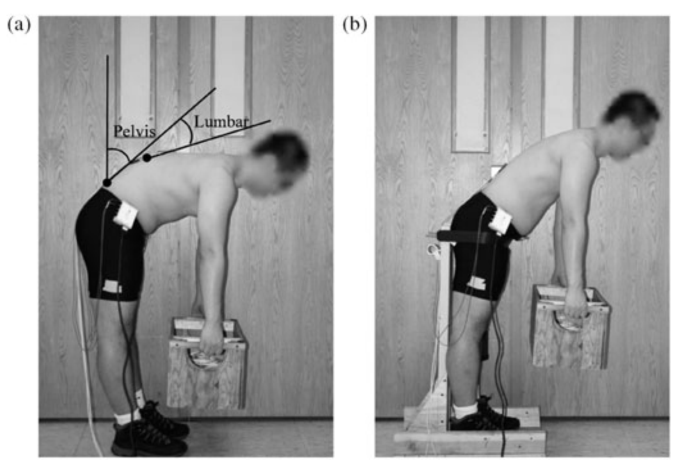

Figure 1. (a) A snapshot during a weightlifting task, the definitions of lumbar and pelvis rotation angles are also demonstrated; (b) demonstration of the static weight holding task performed during the fatiguing protocol.

2.4 Protocol

Upon arrival, subjects were given a detailed description of the tasks they were required to perform; informed consent forms (approved by the local Institutional Review Board) were then signed. Prior to the data collection, subjects performed a 5-minute warm-up section to stretch muscles and familiarise with the experiment protocol. Motion sensors and surface EMG electrodes were then attached to the designated locations with double-sided tape.

The current experiment required subjects to perform five repetitions of a weight-lifting task both before and after a lumbar extensor muscle fatiguing protocol in order to compare the changes of lumbar–pelvic coordination caused by fatigue (Figure 1(a)). When performing the weightlifting task, subjects were required to start from an upright standing posture and lift a 20 lbs box (right in front of the subjects with the centre of the box 40 cm away from the mid-point of ankles) using a stoop lifting technique where the arms remained straight (Figure 1(a)). During the fatiguing protocol, subjects were secured in a pelvis restriction apparatus and required to hold the same 20 lbs box until exhaustion whilst attempting to maintain trunk flexion at ~45° so that lumbar curvature also remained constant (Figure1 (b)). To assess the lumbar extensor muscle fatigue, measurements of lumbar muscle EMG median frequency were made at four different time points: (1) at the beginning of the experiment, (2) right before the fatiguing protocol, (3) right after the fatiguing protocol and (4) at the end of the experiment (Figure 2). The fatigue measurement task requires subjects to be secured in the pelvis restriction apparatus and maintain a ~45° flexed trunk posture while holding a 20 lbs box for 6 s. The hand load was used to elevate the lumbar extensor muscle activity in order to increase the accuracy of the measurement (De Luca 1997) and the six seconds of sampling duration was chosen based on previous research to both avoid the accumulation of muscle fatigue and ensure the quality of the data (Ning 2011).

2.5 Data processing

2.5.1 EMG median frequency

EMG data from the erector spinae muscle during the performance of fatigue measurement tasks were transferred into frequency domain and passed through a 500 Hz low-pass filter, a 10 Hz high-pass filter and a notch filter at 60 Hz and its aliases; the median point of the frequency spectrum was then calculated and used to quantify the accumulation or recovery of muscle fatigue (De Luca 1997). The median frequency data were used to verify the following goals of the experiment design: (1) the lifting trials prior to the fatiguing protocol do not introduce lumbar extensor muscle fatigue; (2) significant fatigue can be generated during the fatiguing protocol and (3) significant recovery of muscle fatigue does not occur during the performance of lifting tasks after the fatiguing protocol.

2.5.2 CRP and CRP variability

Previous studies have made extensive efforts in investigating the algorithm of CRP (Kurz and Stergiou 2002; Peters et al. 2003; Van Emmerik, and Wagenaar 1996; Seay, Van Emmerik, and Hamill 2011; Selles et al. 2001; Heiderscheit, Hamill, and Van Emmerik 2002; Miller et al. 2008; Lamoth et al. 2002, Hu, Ning, and Nussbaum 2014). In the current study, instantaneous lumbar and pelvic angular positions were obtained from the output of motion sensors, and angular velocities were then derived from the angular position data collected in the time domain (Seay, Van Emmerik, and Hamill 2011). Both angular positions and angular velocities were normalised from -1 to $+1$ corresponding to the minimum and maximum values, respectively, during each lifting task. The lumbar and pelvic phase plane plots were then created using these normalised data (Figure 3(a)). For each motion segment, the instantaneous phase angle was calculated using the phase plane coordinates with the arctangent function (Burgess-Limerick, Abernethy, and Neal 1993). The lumbar–pelvic CRP was

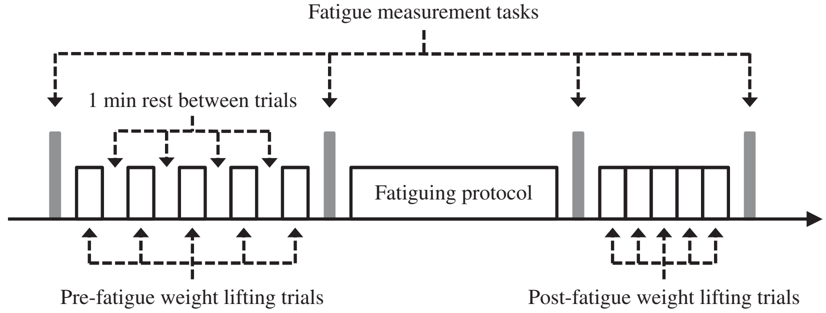

Figure 2. Illustration of the experimental timeline.

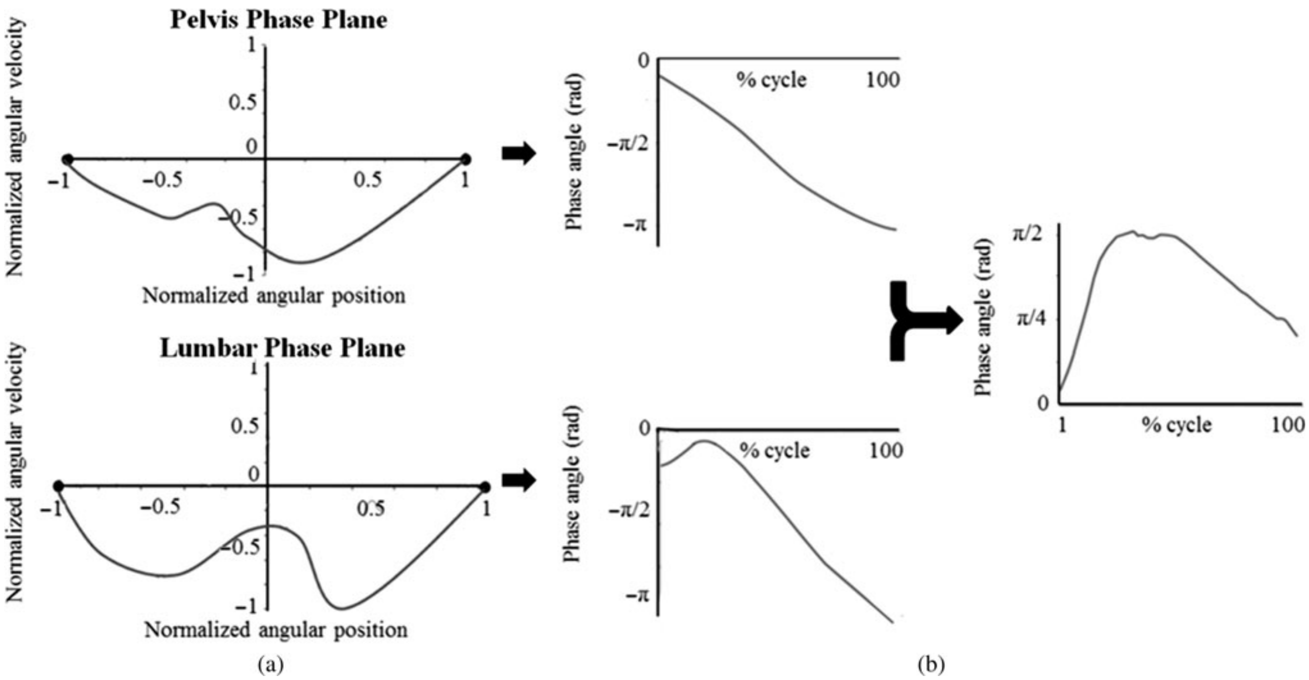

Figure 3. Illustration of CRP calculation: (a) phase plane for pelvic segment and lumbar segment. (b) Phase angle profile for pelvic and lumbar segment and final CRP profile.

defined as the phase angle difference between these two motion segments (Figure 3(b)). A close to 0 rad CRP represents a more "in-phase" motion pattern between the segments and a close to π rad CRP represents a more "out-phase" motion pattern. Previous studies suggested that more in-phase coordination patterns might represent increased protective guarding motions among task performers (Ahern et al. 1988; Selles et al. 2001; Seay, Van Emmerik, and Hamill 2011). CRP variability was defined as the standard deviation of the CRP profile for each trial.

2.5.3 Spinal loading

Although EMG-assisted biomechanical models (Marras and Granata 1997a, 1997b; Sparto and Parnianpour 1999; Jia, Kim, and Nussbaum 2011) can be used to estimate muscle forces, in the current study considering the influence of muscle fatigue on EMG signals, muscle forces were not assessed, and instead, a physical model (Ning, Jin, and Mirka 2012; Ning et al. 2014; Hu et al. 2014) was used to calculate the instantaneous external moment on the L5/S1 joint. In this model, subjects' anthropometric measurements (including body height, weight, etc.) were used in combination with trunk kinematics (i.e. trunk angles, angular velocities and accelerations) to estimate the total moment of upper body imposed on the L5/S1 joint. The mass and centre of mass of body segments were estimated according to previous findings (Mirka et al. 1998). Then the L5/S1 joint moments during the 10th, 20th, 30th … and 100th percentiles (divided based on lifting duration) of weightlifting motion were obtained.

2.6 Statistical analysis

In the current study, all statistical analyses were performed using Minitab (Minitab 15, Minitab Inc., State College, PA, USA). Prior to the analyses, the assumptions of the analysis of variance (ANOVA) procedures (independence of observations, constant variance of residuals and normal distribution of residuals) were checked; variables that did not satisfy all assumptions were transformed to meet all the criteria (Montgomery 2012). The effect of fatigue on each dependent variable was tested using repeated ANOVA. Subjects were set as the blocking factors and lumbar loadings at each 10th percentile of lifting were treated as additional dependent variables. A criteria p-value of 0.05 was used for all statistical analyses.

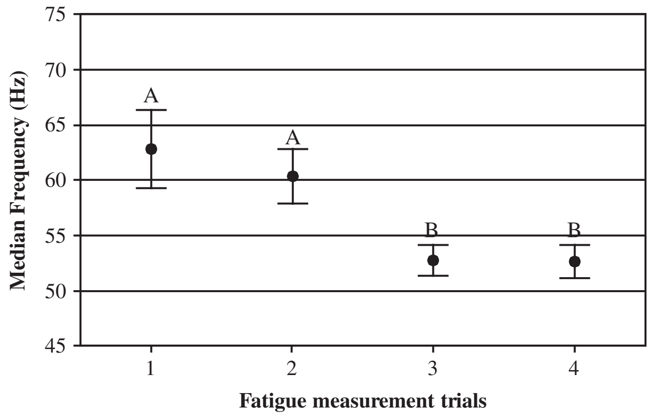

Figure 4. The median frequency of lumbar muscle EMG from fatigue measurement tasks. The sequence of the measurement is specified in Figure 2. Different letters denote angles that are statistically different from one another. Bars indicate the corresponding standard error.

3. Result

3.1 Lumbar extensor muscle fatigue

In the current study, fatigue was characterised by the decrease of median frequency in muscle EMG. Data from fatigue measurement tasks suggested that based on post hoc analyses, overall, no significant muscle fatigue was generated after performing five repetitions of weightlifting tasks prior to the fatiguing protocol. The fatiguing protocol, on the other hand, introduced significant drop of EMG median frequency (on average 10.2 Hz, p-value < 0.001) which demonstrated a clear accumulation of fatigue among lumbar extensor muscles (Elfving et al. 2002); such drop in median frequency remained until the completion of another five repetitions of lifting tasks as shown in Figure 4. These results have collectively demonstrated that the goals of our experiment design were successfully achieved.

3.2 Lumbar–pelvic CRP and CRP variability

The results of our statistical analyses showed that lumbar extensor muscle fatigue significantly affected the lumbar–pelvic CRP during lifting (Figure 5). In general, after the fatiguing protocol, subjects demonstrated significantly smaller average CRP values (i.e. more in-phase lumbar–pelvic coordination). To analyse the lifting motions in greater detail, in addition to the overall pattern, the average CRP values in each quarter (equally divided based on time) of lifting motion were compared (McGorry and Hsiang 1999). In the first quarter of the lifting motion, the CRP remained unchanged after the fatiguing protocol; however, in the other three quarters of lifting, lumbar extensor muscle fatigue significantly reduced the average CRP values. The mean value of CRP variability also decreased after fatigue (pre-fatigue: 0.17 ± 0.015 rad; post-fatigue: 0.15 ± 0.009 rad); however, such decrease was only approaching significance (p-value $= 0.07$).

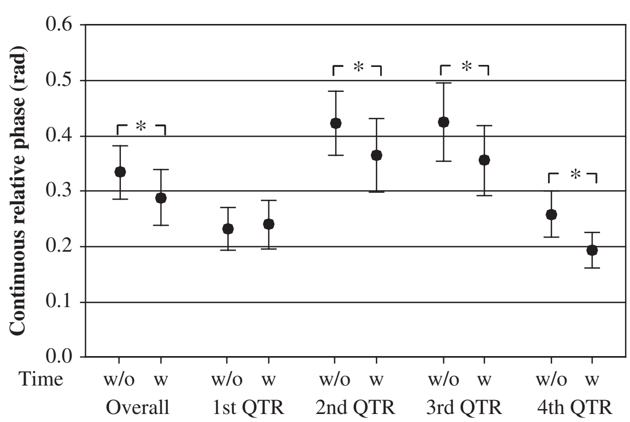

Figure 5. Continuous relative phase of different conditions. Bars indicate the corresponding standard error. In the horizontal axis, 'w' indicates 'with fatigue' and 'w/o' indicates 'without fatigue'.

Table 1. The L5/S1 joint moment during the 10th, 20th, 30th ... and 100th percentiles of weightlifting.

		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Pre Fatigue	Mean (N*m)	143.6	131.5	113.9	95.1	74.1	53.8	36.8	23.8	15.5	12.2
	SD	20.2	21.2	26.5	25.9	24.4	22.5	19.8	15.8	11.6	18.4
Post Fatigue	Mean (N*m)	144.8	134.4	121.9	105.1	86.1	65.4	45.9	29.8	17.9	11.7
	SD	27.9	29.2	26.4	27.5	27.2	24.8	20.8	16.0	11.7	11.4
p-value		0.097	**0.045**	**0.029**	**0.014**	**0.005**	**0.007**	**0.025**	0.09	0.63	0.87

Note: The significance threshold for bold values is 0.05.

3.3 Spinal loading

Significantly larger L5/S1 joint external moment values were consistently observed from 20th to 70th percentiles of lifting motions after lumbar muscle fatigue was introduced (Table 1).

4. Discussion

The purpose of this study was to better understand how lumbar extensor muscle fatigue could elevate the risk of LBP by investigating the changes of lumbar–pelvic coordination during lifting motions before and after lumbar muscle fatigue. Results of this study in general supported our initial hypotheses that with the influence of lumbar extensor muscle fatigue non-symptomatic subjects demonstrated more in-phase lumbar–pelvic coordination and reduced CRP variability.

A number of studies have shown that LBP patients demonstrated more in-phase lumbar–pelvic coordination and reduced lumbar stability (Cholewicki and McGill 1996; Lamoth et al. 2002; Seay, Van Emmerik, and Hamill 2011; Selles et al. 2001; Van Emmerik et al. 1999). Earlier studies also suggested that LBP patients tend to adopt more "protective guarding" motions in order to compensate for the decreased stability and reduce the risk of injury (Marras and Wongsam 1989; Ahern et al. 1988). In-phase lumbar–pelvic coordination is externalised as more unidirectional rotary motion between pelvis and lumbar motion segments. This change of motion pattern could reduce the dynamic complexity of the body and may be viewed as a subconscious protecting mechanism. On the other hand, based on the results of the current study, it is clear that non-symptomatic subjects who developed transient lumbar muscle fatigue adopted more in-phase and less variant lumbar–pelvic motion patterns during lifting tasks. Earlier study reported that certain amount of lumber extensor muscle fatigue could lead to decreased spinal dynamic stability and reduced dynamic complexity (Granata and Gottipati 2008). It is possible that subjects in the current study adopted more in-phase lumbar–pelvic motion pattern to compensate for the decreased lumbar stability.

On the other hand, previous studies discovered strong positive correlation between the magnitude of mechanical loading on the spine and the risk of lower back injury (Granata and Marras 1993; Marras and Granata 1995; Neumann et al. 1999). The results of this study suggested that the muscle fatigue-induced in-phase lumbar–pelvic coordination may compensate the decreased spinal stability; however, such motion pattern significantly increased spinal external loading which could lead to elevated risk of LBP.

Previous studies discovered reduced CRP variability among LBP and other musculoskeletal disorder patients (Van Emmerik et al. 1999). One study found that LBP patients had smaller pelvic–trunk CRP coordination variability during walking than the healthy subjects (Selles et al. 2001). Other studies found similar results among patients with knee pain (Heiderscheit, Hamill, and Van Emmerik 2002) and iliotibial band syndrome (Miller et al. 2008). In addition, one study revealed that LBP patients showed smaller lumbar–pelvic coordination variability with the increase of walking speed (Lamoth et al. 2002). In line with the previous findings, the results of current study found 12% (0.021 rad) decrease of lumbar–pelvic CRP variability during lifting after the fatiguing protocol. However, such reduction was not statistically significant. One possible reason is that compared to walking and running, weightlifting involves much larger range of motion from both lumbar and pelvis segments; as a result, larger kinematic variance can be generated between trials.

The current study has several limitations to be noted. First, only one level of hand load was tested in this study, and it is possible that the changes of hand load could interact with muscle fatigue and influence the lumbar–pelvic coordination during weightlifting. Second, only sagittal symmetric lifting was investigated in the current study. Subjects may demonstrate different lumbar–pelvic coordination when performing more complex asymmetric lifting. Besides, lumbar extensor muscle fatigue was introduced by performing sustained weight holding in a relatively short period of time (e.g. a few minutes). However, previous studies showed that performing dynamic tasks over a longer period of time (e.g. an 8 h shift) can generate muscle fatigue with very different characteristics (Elfving and Dedering 2007) and therefore warrants future investigation. Finally, pre-fatigue and post-fatigue lifting trials were performed adjacently in the same day, and although we did not observe any clear trend in motion pattern changes within the same condition, due to the nature of the current experiment design, the potential influence of learning effect on our results cannot be eliminated.

5. Conclusions

The results of the current study showed that healthy subjects adopt more 'in-phase' lumbar–pelvic motion pattern when experiencing lumbar muscle fatigue. Such change in lumbar–pelvic motion could elevate the L5/S1 joint loading which in turn could increase the risk of LBP. Our results suggest that changes of lumbar–pelvic motion pattern could be used in occupational environment for the identification of lumbar muscle fatigue. In addition, although occasionally experienced lumbar muscle fatigue may be inevitable, effort should be made to avoid prolonged or frequently experienced lumbar extensor muscle fatigue in order to reduce the risk of spinal injury.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ahern, D. K., M. J. Follick, J. R. Council, N. Laser-Wolston, and H. Litchman. 1988. "Comparison of Lumbar Paravertebral EMG Patterns in Chronic Low Back Pain Patients and Non-Patient Controls." *Pain* 34 (2): 153–160. doi:10.1016/0304-3959(88)90160-1.

Bakker, E. W. P., A. P. Verhagen, C. Lucas, H. J. C. M. F. Koning, R. J. de Haan, and B. W. Koes. 2007. "Daily Spinal Mechanical Loading as a Risk Factor for Acute Non-Specific Low Back Pain: A Case-Control Study Using the 24-Hour Schedule." *European Spine Journal* 16 (1): 107–113. doi:10.1007/s00586-006-0111-2.

Baldwin, M. L. 2004. "Reducing the Costs of Work-Related Musculoskeletal Disorders: Targeting Strategies to Chronic Disability Cases." *Journal of Electromyography and Kinesiology* 14 (1): 33–41. doi:10.1016/j.jelekin.2003.09.013.

Biering-sorensen, F. 1984. "1983 Volvo Award in Clinical Science." *Spine* 9 (2): 106–119. doi:10.1097/00007632-198403000-00002.

Burgess-Limerick, R., B. Abernethy, and R. J. Neal. 1993. "Relative Phase Quantifies Interjoint Coordination." *Journal of Biomechanics* 26 (1): 91–94. doi:10.1016/0021-9290(93)90617-N.

Cholewicki, J., and S. M. McGill. 1996. "Mechanical Stability of the In Vivo Lumbar Spine: Implications for Injury and Chronic Low Back Pain." *Clinical Biomechanics* 11 (1): 1–15. doi:10.1016/0268-0033(95)00035-6.

De Luca. 1997. "The Use of Surface Electromyography in Biomechanics." *Journal of Applied Biomechanics* 13: 135–163.

Descarreaux, M., D. Lafond, R. J. Gauthier, H. Centomo, and V. Cantin. 2008. "Changes in the Flexion Relaxation Response Induced by Lumbar Muscle Fatigue." *BMC Musculoskeleton Disorder* 9:9–10.

Elfving, B., and A. Dedering. 2007. "Task Dependency in Back Muscle Fatigue – Correlations Between Two Test Methods." *Clinical Biomechanics* 22 (1): 28–33. doi:10.1016/j.clinbiomech.2006.08.007.

Elfving, B., D. Liljequist, A. Dedering, and G. Németh. 2002. "Recovery of Electromyograph Median Frequency After Lumbar Muscle Fatigue Analysed Using an Exponential Time Dependence Model." *European Journal of Applied Physiology* 88 (1–2): 85–93. doi:10.1007/s00421-002-0685-2.

Fritz, J. M., and S. George. 2000. "The Use of a Classification Approach to Identify Subgroups of Patients With Acute Low Back Pain." *Spine* 25 (1): 106–114. doi:10.1097/00007632-200001010-00018.

Granata, K. P., and P. Gottipati. 2008. "Fatigue Influences the Dynamic Stability of the Torso." *Ergonomics* 51 (8): 1258–1271. doi:10.1080/00140130802030722.

Granata, K. P., and W. S. Marras. 1993. "An EMG-Assisted Model of Loads on the Lumbar Spine During Asymmetric Trunk Extensions." *Journal of Biomechanics* 26 (12): 1429–1438. doi:10.1016/0021-9290(93)90093-T.

Hamill, J., J. M. Haddad, and W. J. Mcdermott. 2000. "Issues in Quantifying Variability From a Dynamical Systems Perspective." *Journal of Applied Biomechanics* 16: 407–418.

Heiderscheit, B. C., J. Hamill, and R. E. A. Van Emmerik. 2002. "Variability of Stride Characteristics and Joint Coordination Among Individuals with Unilateral Patella-Femoral Pain." *Journal of Applied Biomechanics* 18: 110–121.

Hu, B., X. Ning, and A. Nimbarte. 2013a. "Changes of Lumbar Muscle Flexion Relaxation Phenomenon When Standing on Unilaterally Elevated Ground." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 57 (1): 925–928. doi:10.1177/1541931213571205.

Hu, B., X. Ning, and A. Nimbarte. 2013b. "The Changes of Lumbar Muscle Flexion-Relaxation Response Due to Laterally Slanted Ground Surfaces." *Ergonomics* 56 (8): 1295–1303, Proceedings of the Human Factors and Ergonomics Society Annual Meeting 57: 925–928doi:10.1080/00140139.2013.803161.

Hu, B., X. Ning, and M. A. Nussbaum. 2014. "The Influence of Hand Load on Lumbar–Pelvic Coordination During Lifting Task." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 58 (1): 1617–1621. doi:10.1177/1541931214581337.

Hu, B., X. Shan, J. Zhou, and X. Ning. 2014. "The Effects of Stance Width and Foot Posture on Lumbar Muscle Flexion–Relaxation Phenomenon." *Clinical Biomechanics* 29 (3): 311–316. doi:10.1016/j.clinbiomech.2013.12.009.

Jia, B., S. Kim, and M. A. Nussbaum. 2011. "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." *Ergonomics* 41: 437–446.

Kankaanpää, M., S. Taimela, D. Laaksonen, O. Hänninen, and O. Airaksinen. 1998. "Back and Hip Extensor Fatigability in Chronic Low Back Pain Patients and Controls." *Archives of Physical Medicine and Rehabilitation* 79 (4): 412–417. doi:10.1016/S0003-9993(98)90142-3.

Kurz, M. J., and N. Stergiou. 2002. "Effect of Normalization and Phase Angle Calculations on Continuous Relative Phase." *Journal of Biomechanics* 35 (3): 369–374. doi:10.1016/S0021-9290(01)00211-1.

Lamoth, C. J. C., O. G. Meijer, J. M. Wuisman, J. H. Van Dieen, M. F. Levin, and P. J. Beek. 2002. "Pelvis–Thorax Coordination in the Transverse Plane During Walking in Persons With Nonspecific Low Back Pain." *Spine* 27 (4): E92–E99. doi:10.1097/00007632-200202150-00016.

Luo, XuemeiX., RicardoR. Pietrobon, ShawnS. X Sun, Gordon G.G. G. Liu, LloydL. Hey, X. Luo, R. Pietrobon, S. X. Sun, and G. G. Liu. 2003. "Estimates and Patterns of Direct Health Care Expenditures Among Individuals with Back Pain in the United States." *Spine* 29 (1): 79–86. doi:10.1097/01.BRS.0000105527.13866.0F.

Luoto, S., H. Heliövaara, H. Hurri, and H. Alaranta. 1995. "Static back Endurance and the Risk of Low-Back Pain." *Clinical Biomechanics* 10 (6): 323–324. doi:10.1016/0268-0033(95)00002-3.

Maetzel, A., and L. Li. 2002. "The Economic Burden of Low Back Pain: A Review of Studies Published Between 1996 and 2001." *Best Practice & Research. Clinical Rheumatology* 16 (1): 23–30. doi:10.1053/berh.2001.0204.

Manchikanti, L., V. Singh, S. Datta, S. Cohen, and J. Hirsch. 2009. "Comprehensive Review of Epidemiology, Scope, and Impact of Spinal Pain." *Pain Physician* 12: E35.

Marras, William S., Sue A. Ferguson, DeborahD. Burr, Kermit G.K. G. Davis, PurnenduP. Gupta, W. S. Marras, S. A. Ferguson, D. Burr, and K. G. Davis. 2005. "Functional Impairment as a Predictor of Spine Loading." *Spine* 30 (7): 729–737. doi:10.1097/01.brs.0000157459.36970.62.

Marras, W. S., and K. P. Granata. 1995. "A Biomechanical Assessment and Model of Axial Twisting in the Thoraco-Lumbar Spine." *Spine* 20 (13): 1440–1451. doi:10.1097/00007632-199507000-00002.

Marras, W. S., and K. P. Granata. 1997a. "The Development of an EMG-Assisted Model to Assess Spine Loading During Whole-Body Free-Dynamic Lifting." *Journal of Electromyography and Kinesiology* 7 (4): 259–268. doi:10.1016/S1050-6411(97)00006-0.

Marras, W. S., and K. P. Granata. 1997b. "Spine Loading During Trunk Lateral Bending Motions." *Journal of Biomechanics* 30 (7): 697–703. doi:10.1016/S0021-9290(97)00010-9.

Marras, W. S., and P. E. Wongsam. 1989. "Flexibility and Velocity of the Normal and Impaired Lumbar Spine." *Archives of Physical Medicine and Rehabilitation* 67: 213–217.

McGorry, R. W., and S. M. Hsiang. 1999. "The Effect of Industrial Back Belts and Breathing Technique on Trunk and Pelvic Coordination During a Lifting Task." *Spine* 24 (11): 1124–1130. doi:10.1097/00007632-199906010-00012.

Miller, R. H., S. A. Meardon, T. R. Derrick, and J. C. Gillette. 2008. "Continuous Relative Phase Variability During an Exhaustive Run in Runners With a History of Iliotibial Band Syndrome." *Journal of Applied Biomechanics* 24: 262–270.

Mirka, G. A., A. Baker, A. Harrison, and D. Kelaher. 1998. "The Interaction Between Load and Coupling During Dynamic Manual Materials Handling Tasks." *Occupational Ergonomics* 1: 3–11.

Montgomery, D. C. 2012. *Design and Analysis of Experiments*. 8th ed. New York: John Wiley and Sons.

Moore, B. D., J. Drouin, B. M. Gansneder, and S. J. Shultz. 2002. "The Differential Effects of Fatigue on Reflex Response Timing and Amplitude in Males and Females." *Journal of Electromyography and kinesiology* 12 (5): 351–360. doi:10.1016/S1050-6411(02)00032-9.

Muslim, K., B. Bazrgari, B. Hendershot, N. Toosizadeh, M. A. Nussbaum, and M. L. Madigan. 2013. "Disturbance and Recovery of Trunk Mechanical and Neuromuscular Behaviors Following Repeated Static Trunk Flexion: Influences of Duration and Duty Cycle on Creep-Induced Effects." *Applied Ergonomics* 44 (4): 643–651. doi:10.1016/j.apergo.2012.12.004.

Neumann, W. P., R. P. Wells, R. W. Norman, D. M. Andrews, J. Frank, H. S. Shannon, and M. S. Kerr. 1999. "Comparison of Four Peak Spinal Loading Exposure Measurement Methods and their Association with Low-Back Pain." *Scandinavian Journal of Work, Environment & Health.* 25 (5): 404–409. doi:10.5271/sjweh.452.

Ning, X. 2011. "Ecvelopment of a New Work-Rest Scheduling Model Based on Inventory Control Theory." Graduate Theses and Dissertations, Paper 10086.

Ning, X., S. Haddad, O. Jin, and G. A. Mirka. 2011. "Influence of Asymmetry on the Flexion Relaxation Response of the Low Back Musculature." *Clinical Biomechanics* 26 (1): 35–39. doi:10.1016/j.clinbiomech.2010.08.012.

Ning, X., S. Jin, and G. A. Mirka. 2012. "Describing the Active Region Boundary of EMG-Assisted Biomechanical Models of the Low Back." *Clinical Biomechanics* 27 (5): 422–427. doi:10.1016/j.clinbiomech.2011.11.003.

Ning, X., J. Zhou, B. Dai, and M. Jaridi. 2014. "The Assessment of Material Handling Strategies in Dealing with Sudden Loading: The Effects of Load Handling Position on Trunk Biomechanics." *Applied Ergonomics* 45 (6): 1399–1405. doi:10.1016/j.apergo.2014.03.008.

Norman, R., R. Wells, P. Neumann, J. Frank, H. Shannon, and M. Kerr. 1998. "A Comparison of Peak vs Cumulative Physical Work Exposure Risk Factors for the Reporting of Low Back Pain in the Automotive Industry." *Clinical Biomechanics* 13 (8): 561–573. doi:10.1016/S0268-0033(98)00020-5.

Peters, B. T., J. M. Haddad, B. C. Heiderscheit, R. E. Van Emmerik, and J. Hamill. 2003. "Limitations in the Use and Interpretation of Continuous Relative Phase." *Journal of Biomechanics* 36 (2): 271–274. doi:10.1016/S0021-9290(02)00341-X.

Rodrigo, A. S., R. S. Goonetilleke, and S. Xiong. 2013. "Load Distribution to Minimise Pressure-Related Pain on Foot: A Model." *Ergonomics* 56 (7): 1180–1193. doi:10.1080/00140139.2013.797111.

Roy, S. H., C. J. De Luca, L. Snyder-Mackler, M. S. Emley, R. L. Crenshaw, and J. P. Lyons. 1990. "Fatigue, Recovery, and Low Back Pain in Varsity Rowers." *Medicine and Science in Sports and Exercise* 22 (4): 463???469–469. doi:10.1249/00005768-199008000-00008.

Scholz, J. P. 1990. "Dynamic Pattern Theory-Some Implications for Therapeutics." *Physical Therapy* 70: 827–843.

Schöner, G., W. Y. Jiang, and J. A. S. Kelso. 1990. "A Synergetic Theory of Quadrupedal Gaits and Gait Transitions." *Journal of Theoretical Biology* 142 (3): 359–391. doi:10.1016/S0022-5193(05)80558-2.

Seay, J. F., R. E. A. Van Emmerik, and J. Hamill. 2011. "Low Back Pain Status Affects Pelvis–Trunk Coordination and Variability During Walking and Running." *Clinical Biomechanics* 26 (6): 572–578. doi:10.1016/j.clinbiomech.2010.11.012.

Selles, R. W., R. C. Wagenaar, T. H. Smit, and P. I. J. M. Wuisman. 2001. "Disorders in Trunk Rotation During Walking in Patients With Low Back Pain: A Dynamical Systems Approach." *Clinical Biomechanics* 16 (3): 175–181. doi:10.1016/S0268-0033(00)00080-2.

Shum, G. L. K., J. Crosbie, and R. Y. W. Lee. 2005. "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 (17): 1998–2004. doi:10.1097/01.brs.0000176195.16128.27.

Sparto, P. J., and M. Parnianpour. 1999. "An Electromyography-Assisted Model to Estimate Trunk Muscle Forces During Fatiguing Repetitive Trunk Exertions." *Journal of Spinal Disorders and Techniques* 12: 509–518.

Tafazzol, A., N. Arjmand, A. Shirazi-Adl, and M. Parnianpour. 2014. "Lumbopelvic Rhythm During Forward and Backward Sagittal Trunk Rotations: Combined In Vivo Measurement With Inertial Tracking Device and Biomechanical Modeling." *Clinical Biomechanics* 29 (1): 7–13. doi:10.1016/j.clinbiomech.2013.10.021.

Van Emmerik, R. E. A., and R. C. Wagenaar. 1996. "Effects of Walking Velocity on Relative Phase Dynamics in the Trunk in Human Walking." *Journal of Biomechanics* 29 (9): 1175–1184. doi:10.1016/0021-9290(95)00128-X.

Van Emmerik, Richard E. A. R. E., Robert C. R. C. Wagenaar, AniaA. Winogrodzka, Erik C.E. C. Wolters, R. E. A. Van Emmerik, R. C. Wagenaar, and A. Winogrodzka. 1999. "Identification of Axial Rigidity During Locomotion in Parkinson Disease." *Archives of Physical Medicine and Rehabilitation* 80 (2): 186–191. doi:10.1016/S0003-9993(99)90119-3.

Wilder, D. G., A. R. Aleksiev, M. L. Magnusson, M. H. Pope, K. F. Spratt, and V. K. Goel. 1996. "Muscular Response to Sudden Load." *Spine* 21 (22): 2628–2639. doi:10.1097/00007632-199611150-00013.