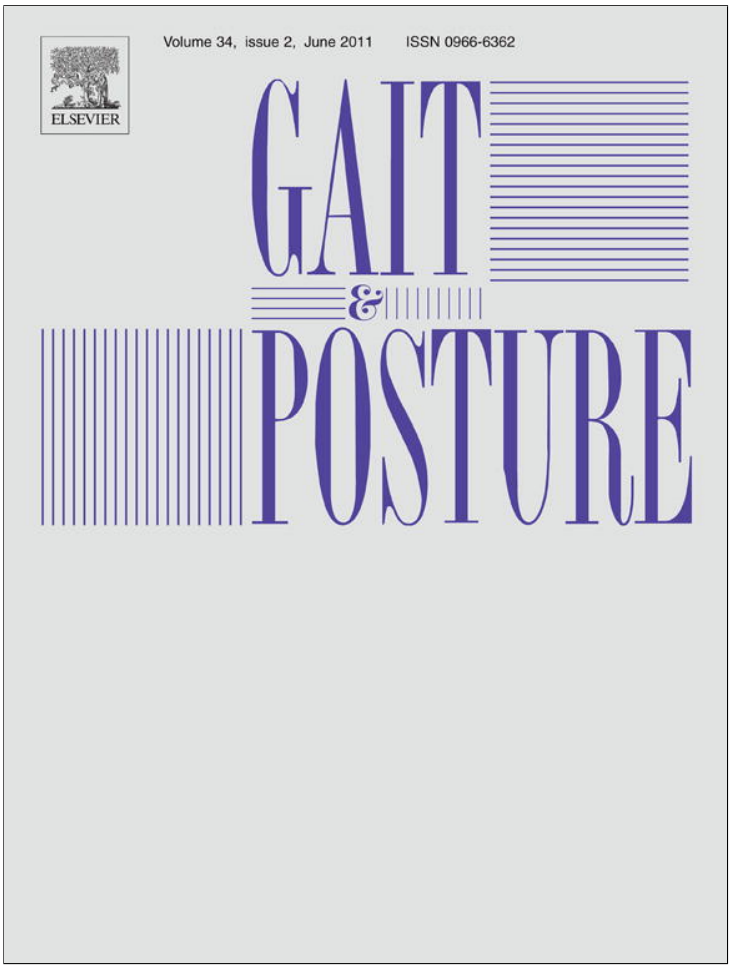

Gait & Posture 34 (2011) 222–226

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Comparison of 3D spinal motions during stair-climbing between individuals with and without low back pain

Jung Keun Lee [a,*], Geoffrey T. Desmoulin [b,c], Aslam H. Khan [b], Edward J. Park [a]

[a] Mechatronic Systems Engineering, School of Engineering Science, Simon Fraser University, 250-13450 102nd Avenue, Surrey, British Columbia V3T 0A3, Canada
[b] Optima Health Solutions International Corp. (KKT International), 308-828 West 8th Avenue, Vancouver, British Columbia V5Z 1E2, Canada
[c] Department of Mechanical and Manufacturing Engineering, Schulich School of Engineering, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada

ARTICLE INFO

Article history:
Received 7 November 2010
Received in revised form 21 April 2011
Accepted 5 May 2011

Keywords:
3D spinal motion
Stair-climbing
Low back pain
Inertial sensor

ABSTRACT

In spite of the importance of stair-climbing (SC) as an activity of daily living, 3D spinal motion during SC has not been investigated in association with low back pain (LBP). The purpose of this research is to investigate the differences of the spinal motions during SC between an LBP group and a healthy control group, in order to provide insight into the LBP effect on the spinal motions. During two types of SC tests (single and double step SCs), we measured 3D angular motions (flexion/extension, lateral bending, and twist) of the pelvis, lumbar spine and thoracic spine using an inertial sensing-based, portable spinal motion measurement system. For the nine motion variables (i.e. three anatomical planes × three segments), range of motions (ROM) and movement patterns were compared to determine the differences between the two groups. It was found that the only variable having the p-value of a t-test lower than 0.05 was the flexion/extension of the lumbar spine in both SCs (i.e. the LBP group's ROM < the control group's ROM). Although the strength of this finding is limited due to the small number of subjects (i.e. 10 subjects for each group) and the small ROM differences between the groups, the comparison result of the t-test along with the motion pattern shows that the effect of LBP during SC may be localized to the lumbar spinal flexion/extension, making it an important measure to be considered in the rehabilitation and treatment of LBP patients.

1. Introduction

Quantitative assessment of low back functional motion is critical to facilitate low back pain (LBP) treatment [1]. While LBP patients typically do not exhibit obvious abnormalities in static conditions, abnormalities of the spine might be revealed by the range of motion (ROM) in dynamic conditions and abnormal motion patterns [2]. Therefore, spinal motion measurement during dynamic conditions may help identify differences between individuals with and without LBP, which could lead to more targeted and improved treatment strategies aimed at regaining normal motion.

As a specific type of activities of daily living, stair-climbing (SC) requires the recruitment of different muscles and more effort than level walking; thus, exhibits unique biomechanical characteristics [3]. In the literature, however, staircase walking study has been focused on lower-limb motions [3,4], while spinal angular kinematics has been focused on level or inclined surface walking conditions [5–7]. Consequently, the spinal motion during SC received little attention and, more importantly, it has not yet been investigated in association with LBP.

The purpose of this research is to investigate the differences of the dynamic spinal motions during stair-climbing between an LBP group and a healthy control group, in order to provide insight into the LBP effect on the spinal motions.

2. Methods

2.1. Subjects and test procedure

We recruited 10 LBP patients (the LBP group – six males and four females; mean age 43.2 (SD 12.5) years; height 175.9 (7.1) cm; weight 73.8 (11.4) kg) and 10 healthy people (the control group – seven males and three females; age 35.9 (16.6) years; height 175.2 (8.6) cm; weight 75.7 (12.3) kg). There were no significant differences between the two groups regarding age, weight and height ($p > 0.05$). The inclusion criteria for the LBP subjects were medical diagnosis of non-specific LBP (musculoskeletal or discogenic origin) with pain and symptoms persisting for longer than six months and stair-climbing without an aid. The exclusion criteria were history of spinal surgery, fracture/dislocation of the vertebral column, inflammatory joint disease, and neurological signs. The functional ability of the LBP subjects was evaluated using the revised Oswestry Disability Index [8] (Table 1). The control subjects satisfied requirements of not having a history of back pain, balance disabilities, or leg pains.

The SC test was divided into a single step SC (SSC), where the subjects climbed one step at a time, and a double step SC (DSC), where the subjects covered two steps in a single stride instead, all at some self-selected climbing rate. Since the DSC

* Corresponding author. Tel.: +1 778 782 8577; fax: +1 778 782 7514.
E-mail address: jkl25@sfu.ca (J.K. Lee).

0966-6362/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2011.05.002

Table 1
Mean (SD) of the scores of each section in the revised Oswestry Disability questionnaire.

Section	Score[a]
1. Pain intensity	2.5 (1.3)
2. Personal care	1.8 (0.8)
3. Lifting	2.9 (1.2)
4. Walking	2.0 (1.3)
5. Sitting	2.3 (1.3)
6. Standing	1.9 (1.1)
7. Sleeping	2.2 (1.2)
8. Social life	1.8 (1.1)
9. Travelling	2.0 (0.8)
10. Changing degree of pain	3.3 (0.9)
Total[b]	45.4 (19.6)%

[a]Each section has six statements where the first and last statements correspond to the scores 0 (no disability) and 5 (highest disability), respectively.
[b]The total score has been calculated as the sum of 10 section scores times two, which varies from 0 to 100.

requires the subjects to move double the distance both vertically and horizontally, it exaggerates their leg movements and amplifies their spinal motions accordingly. The tests were performed at an outdoor staircase consisted of 13 steps, each of which is 30 cm long and 17 cm high. Ten cycles were collected for each test. This study was approved by the Office of Research Ethics of the Simon Fraser University.

2.2. Measurement system

To investigate the 3D spinal movements in relation to the stride cycle percentage, the measurement system is comprised of two subsystems: a spinal motion measurement part and a stride cycle detection part. First, the spinal motion measurement part consisted of three inertial/magnetic MTx sensors (Xsens Technologies B.V., Netherlands) attached onto the skin of the subject at the upper trunk (T1), middle trunk (T12) and pelvis (S1) with elastic Velcro strapping (Fig. 1a). Each MTx consists of a tri-axial accelerometer, a tri-axial gyroscope, and a tri-axial magnetometer and provides a 3D orientation through Xsens' Kalman filter-based sensor fusion algorithm. Second, for the stride cycle detection, two Xsens' MT9 sensors were attached onto each shank above the ankle and only one axis gyroscope signal (perpendicular to the sagittal plane) from each MT9 was used. For battery power and data transfer, both MTx and MT9 sensors were hard wired to their respective digital data bus systems (Xsens' XBus) which were put in a waist belt bag. Subsequently, the MTx and MT9 XBuses were interfaced with a laptop via a wireless Bluetooth connection at 50 Hz sampling rate and an RS-232 serial connection at 100 Hz, respectively.

2.3. Analysis

In order to get an orientation of a body segment frame B (e.g., T1, T12, or S1) with respect to the global frame G, ${}^{G}_{B}R$, the coordinate transformation was performed: ${}^{G}_{B}R = {}^{G}_{F}R\,{}^{F}_{S}R\,{}^{S}_{B}R$, where S and F represent a sensor frame (e.g., up, mid, or low) and an Earth-fixed reference frame of each sensor, respectively. Fig. 1b illustrates the above coordinate frames in our sensor setup. In the transformation, first, ${}^{G}_{F}R$ is constant since both G and F are Earth-fixed frames that can be initially obtained through an automatic coordinate calibration procedure performed in a static upright standing state prior to each test. Next, ${}^{F}_{S}R$ is computed by the sensor's software. Last, ${}^{S}_{B}R$ is also set as constant by assuming that negligible relative orientation change of the sensors occurs with respect to the body segments. After calculating ${}^{G}_{B}R$ for each segment, the relative orientations of T12 with respect to S1 (${}^{S1}_{T12}R$) and of T1 with respect to T12 (${}^{T12}_{T1}R$) can be obtained, representing the postures of the lumbar and thoracic spines, respectively. Note that ${}^{G}_{S1}R$ represents the posture of the pelvis with respect to the global frame. These orientations were then transformed into flexion/extension, lateral bending, and axial twist using the tilt/twist algorithm [9]. In the stride cycle detection part, the shank-attached gyroscopes of the MT9 sensors measure anterior–posterior shank angular velocities and provide sharp peaks occurring when the foot hits the ground so that we can localize the initial contact points [10]. Next, each stride cycle from right initial contact to the next one was time-normalized to represent a cycle percentage. Then, the ranges of motion (peak-to-peak amplitudes) were calculated for nine motion variables in total (i.e. three anatomical planes × three three segments). A Student's t-test was used to see which motion variables are important in characterizing the spinal motions of LBP patients in terms of the ROMs. With regards to the motion patterns, the mean values of the variables for each subject were subtracted from the data to make the superimposed data curves centered at 0°, which removes unnecessary variations introduced by different initial angles of each subjects.

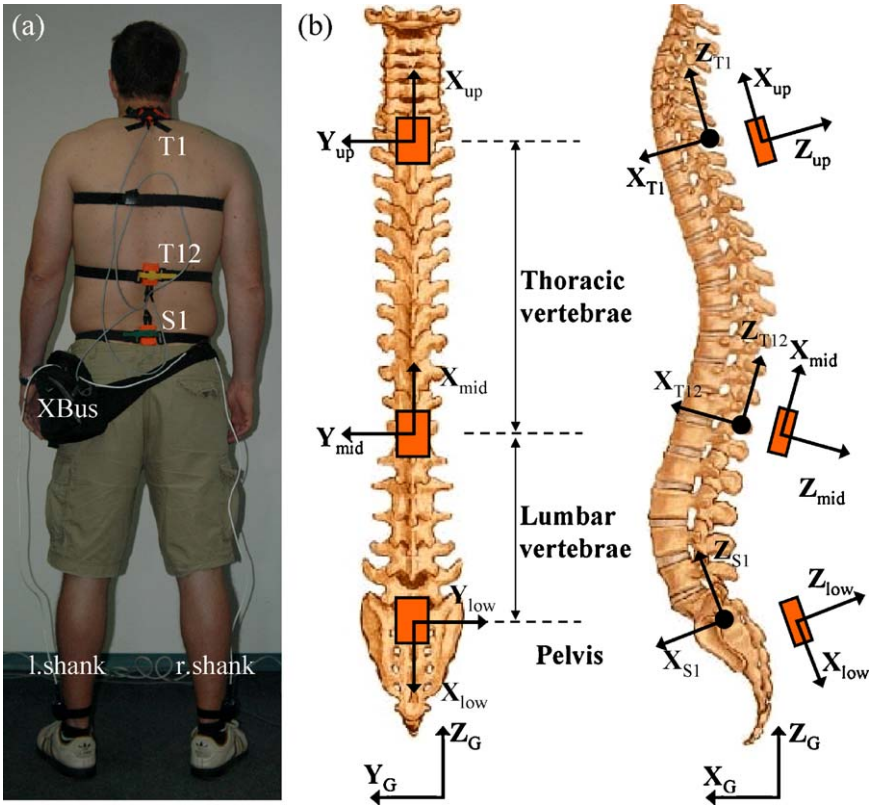

Fig. 1. (a) System configuration comprised of the spinal motion measurement part (three MTx sensors on T1, T12, and S1) and the stride cycle detection part (two MT9 sensors on the shanks). (b) Segmental regions of the measurement divided by the pelvis, lumbar spine and thoracic spine, and the coordinate relationship between the sensor frames and the body frames of three vertebrae locations from the posterior view (left) and the left lateral view (right).

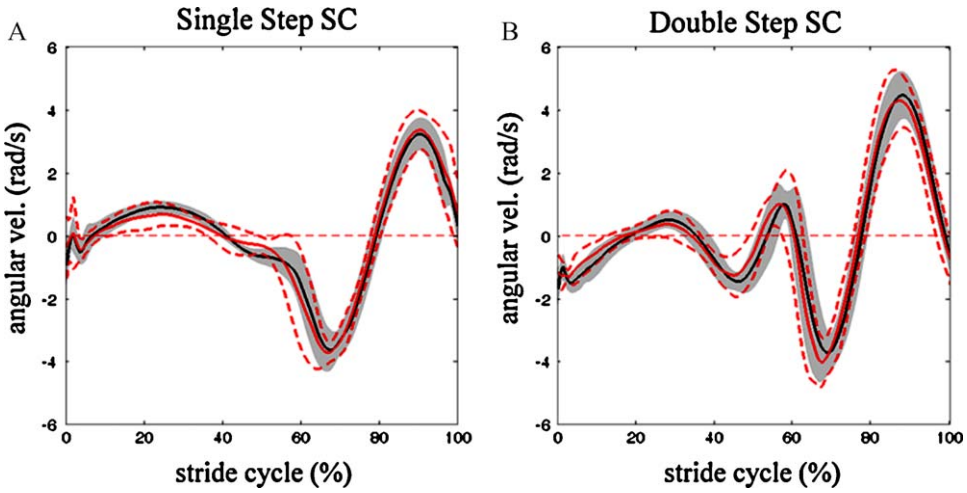

Fig. 2. Comparisons of the right shank angular velocities. The thick red solid and dotted lines are the means and one standard deviation bands for the LBP group and the black lines and shaded regions are the means and one standard deviation bands for the control group. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

3. Results

The stride times of the control group and the LBP group were mean 1.18 (SD 0.10) s and 1.22 (0.24) s during SSC, and 1.53 (0.14) s and 1.59 (0.27) s during DSC. Also, Fig. 2 shows the similar angular velocity patterns of the shanks between the two groups. Hence, the two groups did not show significant differences in strides from the spatio-temporal point of view. In Table 2, it is shown that, in the nine motion variables, the only variable having *p*-value lower than 0.05 was the flexion/extension ROM of the lumbar spine in both SCs (i.e. the LBP group's ROM < the control group's ROM) while the majority of the *p*-values for the other variables were over 0.5. Fig. 3 shows the comparisons of the resulting spinal motion patterns between the two groups. The two groups generally exhibited similar motion patterns (i.e. similar time histories of falling and rising trends in the curves) as long as the patterns were recognizable. In overall, the lateral bendings showed the most recognizable patterns (i.e. high repeatability). The lateral bending motion patterns of the pelvis were closely mirrored with those of the lumbar and thoracic spines in both SC tests (i.e. the opposite movement directions). Meanwhile, the control group produced patterns of the letter 'W' in the lumbar spinal sagittal motion during both SCs. However, the LBP group produced the 'W' pattern only during DSC, while producing an irregular pattern during SSC.

4. Discussion

In the literature, it has been reported that LBP patients tend to walk more slowly than pain-free individuals [11]. However, the characteristic was not observed in our study. This may be related to our one time testing rather than long term monitoring. Instead, the two groups had similar stepping patterns (Fig. 2) and speeds, which may minimize any variance in the spinal motion with respect to gait and show the LBP effects more clearly.

The flexion/extension of the lumbar spine is of our particular interest due to the sole low *p*-value (<0.05) among the nine variables in Table 2 (i.e. the relative differences between the groups are 37% in SSC and 33% in DSC). In terms of the segmental region, the difference in the lumbar spine motion in comparison to those of the pelvis and thoracic spine motions could be expected. This is because the lumbar spine would be the most directly affected region by LBP within the three regions. However, in terms of the anatomical planes, the difference in the sagittal plane motion of the lumbar spine is an interesting finding. This is because, in the case of level walking, the sagittal plane motion has been known to have the smallest ROM and lowest repeatability in comparison to the motions in the other two planes, thus providing less biological information [6,12]. However, this is not the case in stair-climbing. The lumbar spinal flexion/extension ROM during staircase walking was increased in comparison to that during level walking from the previous studies (e.g., mean ROMs 3.5° in [6] and 3.8° in [13]). More importantly, the LBP group had much smaller flexion/extension ROM of their lumbar spine than the control group. We can postulate that the LBP patients co-contract their spine/torso muscles to increase the spinal stiffness and hold a relatively steady position since this motor recruitment strategy decreases painful spinal motions [14]. Considering the typical phases of stair-climbing activity composed of weight acceptance, pull-up, and forward continuation, it is reasonable that the sagittal plane

Table 2
Comparison of ROM from the SC tests. Mean (SD) for the control group/the LBP group (right) and the *p*-value from a Student's *t*-test (left) during the single step and double step SC tests. The * mark indicates $p < 0.05$ between the control and LBP groups.

Motion variables		Single step SC		Double step SC	
Flex./ext. (°)	Pelvis	6.0 (1.7)/4.7 (0.9)	0.053	17.6 (3.7)/14.6 (4.4)	0.128
	Lumbar spine	7.2 (2.1)/4.9 (2.3)	**0.034***	12.9 (3.9)/9.3 (3.1)	**0.032***
	Thoracic spine	4.9 (1.5)/4.8 (1.8)	0.843	12.5 (4.1)/11.7 (5.3)	0.715
Lat. bend. (°)	Pelvis	9.2 (3.4)/8.8 (3.2)	0.796	19.0 (3.6)/19.7 (3.7)	0.674
	Lumbar spine	8.2 (3.4)/7.0 (2.3)	0.346	14.5 (4.6)/15.4 (4.4)	0.669
	Thoracic spine	7.4 (2.7)/8.0 (3.2)	0.629	11.8 (3.8)/13.1 (5.8)	0.549
Twist (°)	Pelvis	7.8 (3.5)/8.1 (2.7)	0.844	11.1 (4.4)/9.4 (1.7)	0.256
	Lumbar spine	10.4 (3.5)/10.8 (4.1)	0.813	10.7 (4.3)/10.3 (4.8)	0.847
	Thoracic spine	6.0 (1.1)/5.8 (1.4)	0.832	9.2 (2.0)/8.4 (2.4)	0.458

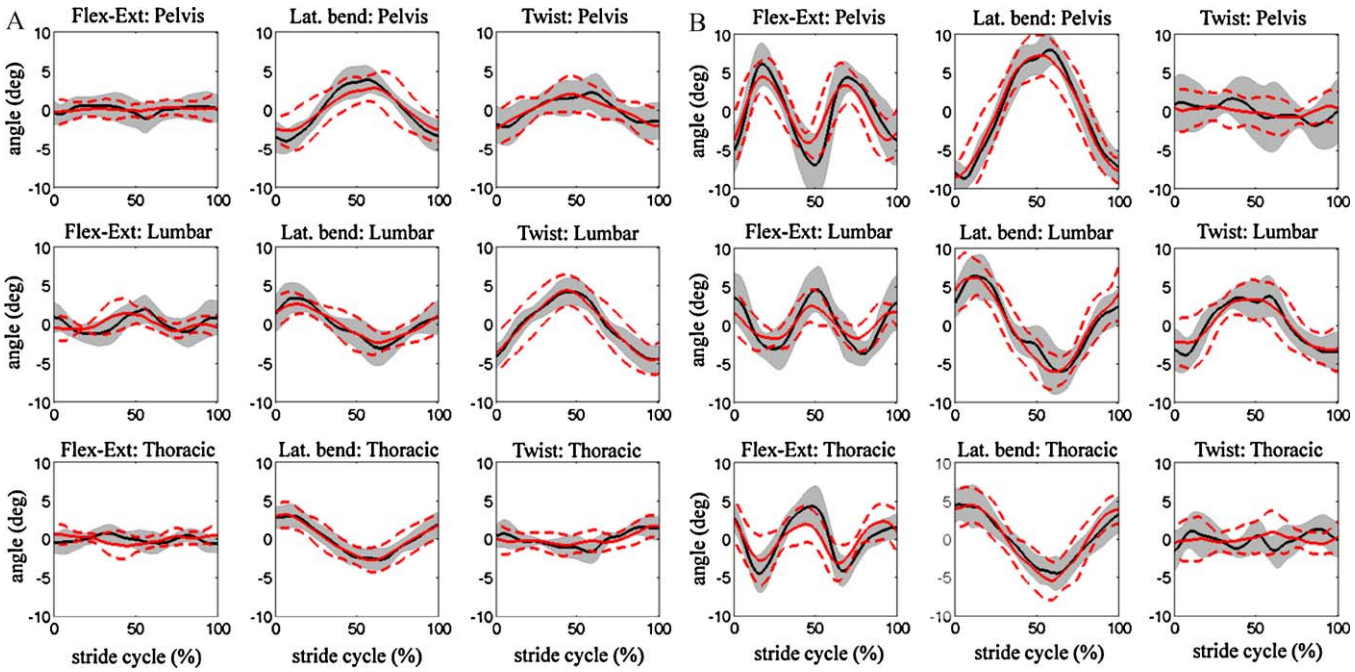

Fig. 3. Comparisons of the tilt/twist angles. (a) and (b) are from the single step and double step SC tests, respectively. The thick red solid and dotted lines are the means and one standard deviation bands for the LBP group and the black lines and shaded regions are the means and one standard deviation bands for the control group. For each plots, the left, middle, and right columns are the flexion/extension angles, the lateral bending angles, and the twist angles, respectively; and the top, middle, and bottom rows are the motions of the pelvis, lumbar spine, and thoracic spine, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

motions play more important role than other plane motions in satisfying the biomechanical requirements of stair-climbing as compared to level walking. Accordingly, the sagittal plane motions possibly have more chances to be affected by the LBP. With regards to the lateral bendings of the pelvis and the lumbar spine, the characteristic of their opposite movement directions is in a good agreement with the results in [6,12], albeit the test conditions in [6,12] were level walking instead of stair-climbing. Also, the high motion repeatability of the lateral bendings of the pelvis and the lumbar spine observed in our results has been already reported in literature. Based on their high repeatability (i.e. subsequently the high reliability), Taylor et al. [15] expected them to have the greater potential in distinguishing the LBP individuals from the controls. However, our comparison results between the two groups in terms of ROM in Table 2 and motion patterns in Fig. 3 indicate that the high repeatability of the lateral bendings does not necessarily mean a high distinguishing ability. Note that, although this study provides clinically important information in the spinal kinematics by showing the ranges and patterns of spinal motions of the two groups, statistical significance of the comparison results may not be attainable due to the limitations of the small number of subjects and the small ROM differences between the groups, requiring further investigations with a larger population and test–retest reliability determination.

This work is facilitated by the use of the inertial sensing-based, portable spinal motion measurement system. While optical tracking is sophisticated and the most prevalent, the motion capture is confined to the controlled lab setting, which is a critical drawback particularly in staircase walking studies. Inertial sensors are not constrained by the *in-the-lab limitation* due to their 'self-contained' property. In terms of the orientation accuracy calculated from the inertial/magnetic sensor signals, the MTx sensors that we employed have an accuracy specification of 2° root mean square in dynamic motion. Also, our previous work [16] on the spinal motion measurement using the MT9 sensors showed an orientation error of 3.1° in roll, 0.3° in pitch, and 1.4° in yaw (verified by a VICON optical motion capture system). However, the case of the system being operated in a magnetically disturbed environment is potentially problematic as the magnetometer signals can be distorted (i.e. ${}^{G}_{F}R$ in Section 2.3 can be changed), requiring a calibration procedure such as magnetic field mapping, otherwise resulting in the heading direction errors [17]. For this reason, we performed the tests in a magnetically homogeneous environment (i.e. outside) to ensure minimal magnetic disturbances.

This study compared the ranges and patterns of pelvic and spinal motions during stair-climbing between the LBP patients and healthy subjects. Our results showed that the lumbar spinal flexion/extension was the only distinctive variable between the LBP and control groups in the 3D pelvic and spinal motions, implying the localized effect of LBP during stair-climbing. This makes the variable a clinically important measure to be further investigated for the LBP treatment.

Acknowledgements

This study was partially funded by an operating grant from Optima Health Solutions International Corp. (KKT International) and matched through the MITACS ACCELERATE graduate research internship program. The authors would like to thank Ian Bercovitz and Matthew Lee for supporting the data analysis.

Conflict of interest statement

The authors declare that they have no conflict of interest.

References

[1] Marras WS, Ferguson SA, Gupta P, Bose S, Parnianpour M, Kim JY, et al. The quantification of low back disorder using motion measures. Methodology and validation. Spine 1999;24(20):2091–100.
[2] Bogduk N, Mercer S. Biomechanics of the cervical spine. I. Normal kinematics. Clin Biomech 2000;15(9):633–48.

[3] Riener R, Rabuffetti M, Frigo C. Stair ascent and descent at different inclinations. Gait Posture 2002;15(1):32–44.
[4] Nadeau S, McFadyen BJ, Malouin F. Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking? Clin Biomech 2003;18(10):950–9.
[5] Chan P, Wong H, Goh J. The repeatablity of spinal motion of normal and scoliotic adolescents during walking. Gait Posture 2006;24(2):219–28.
[6] Crosbie J, Vachalathiti R, Smith R. Patterns of spinal motion during walking. Gait Posture 1997;5(1):6–12.
[7] Vogt L, Banzer W. Measurement of lumbar spine kinematics in incline treadmill walking. Gait Posture 1999;9(1):18–23.
[8] Hudson-Cook N, Tomes-Nicholson K, Breen A. A revised Oswestry disability questionnaire. In: Roland M, Jenner JR, editors. Back pain: new approaches to rehabilitation and education. Manchester: Manchester University Press; 1989. p. 187–204.
[9] Crawford NR, Yamaguchi GT, Dickman CA. A new technique for determining 3-D joint angles: the tilt/twist method. Clin Biomech 1999;14(3):153–65.
[10] Aminian K, Najafi B, Bula C, Leyvraz P, Robert P. Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes. J Biomech 2002;35(5):689–99.
[11] Spenkelink C, Hutten M, Hermens H, Greitemann B. Assessment of activities of daily living with an ambulatory monitoring system: a comparative study in patients with chronic low back pain and nonsymptomatic controls. Clin Rehabil 2002;16(1):16–26.
[12] Thurston AJ, Harris JD. Normal kinematics of the lumbar spine and pelvis. Spine 1983;8(2):199–205.
[13] Taylor N, Goldie P, Evans O. Angular movements of the pelvis and lumbar spine during self-selected and slow walking speeds. Gait Posture 1999;9(2):88–94.
[14] Kravitz E, Moore M, Glaros A. Paralumbar muscle activity in chronic low back pain. Arch Phys Med Rehabil 1981;62(4):172–6.
[15] Taylor N, Evans O, Goldie P. Reliability of measurement of angular movements of the pelvis and lumbar spine during treadmill walking. Physiother Res Int 2001;6(4):205–23.
[16] Goodvin C, Park EJ, Huang K, Sakaki K. Development of a real-time three-dimensional spinal motion measurement system for clinical practice. Med Biol Eng Comput 2006;44(12):1061–75.
[17] de Vries W, Veeger H, Baten C, van der Helm F. Magnetic distortion in motion labs, implications for validating inertial magnetic sensors. Gait Posture 2009;29(4):535–41.