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ORIGINAL ARTICLE

Energetics and mechanics of walking in patients with chronic low back pain and healthy matched controls

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Abstract
Purpose Walking in patients with chronic low back pain (cLBP) is characterized by motor control adaptations as a protective strategy against further injury or pain. The purpose of this study was to compare the preferred walking speed, the biomechanical and the energetic parameters of walking at different speeds between patients with cLBP and healthy men individually matched for age, body mass and height.
Methods Energy cost of walking was assessed with a breath-by-breath gas analyser; mechanical and spatiotemporal parameters of walking were computed using two inertial sensors equipped with a triaxial accelerometer and gyroscope and compared in 13 men with cLBP and 13 control men (CTR) during treadmill walking at standard (0.83, 1.11, 1.38, 1.67 m s^{-1}) and preferred (PWS) speeds. Low back pain intensity (visual analogue scale, cLBP only) and perceived exertion (Borg scale) were assessed at each walking speed.
Results PWS was slower in cLBP [1.17 (SD = 0.13) m s^{-1}] than in CTR group [1.33 (SD = 0.11) m s^{-1}; $P = 0.002$]. No significant difference was observed between groups in mechanical work ($P \geq 0.44$), spatiotemporal parameters ($P \geq 0.16$) and energy cost of walking ($P \geq 0.36$). At the end of the treadmill protocol, perceived exertion was significantly higher in cLBP [11.7 (SD = 2.4)] than in CTR group [9.9 (SD = 1.1); $P = 0.01$]. Pain intensity did not significantly increase over time ($P = 0.21$).
Conclusions These results do not support the hypothesis of a less efficient walking pattern in patients with cLBP and imply that high walking speeds are well tolerated by patients with moderately disabling cLBP.

Keywords Biomechanics · Gait · Human locomotion · Inverted pendulum · Pain

Abbreviations
BMI Body mass index
cLBP Chronic low back pain
COM Centre of body mass
CTR Control
*C*w Energy cost of walking
IPAQ International physical activity questionnaire
ODI Oswestry disability index
OWS Optimal walking speed
PWS Preferred walking speed
TSK Tampa scale for kinesiophobia
VAS Visual analogue scale
$\dot{V}CO_2$ Carbon dioxide output
$\dot{V}O_2$ Oxygen uptake
*W*ext External mechanical work
*W*int Internal mechanical work
*W*tot Total mechanical work

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Introduction

Chronic low back pain (cLBP) is a common problem throughout the world, which has a huge impact at the individual, family, community, and societal levels (Hoy et al. 2010). The typical pattern is to avoid movements or activities that exacerbate pain (Leeuw et al. 2007). Although studies comparing the overall activity level between patients with cLBP and controls are inconsistent, the distribution of physical activity over the course of a day seems to be different (Griffin et al. 2012). The recent literature suggests that individuals develop motor control strategies at multiple levels of the motor system that have short-term benefit, but with potential harmful consequences if maintained in the long term (Hodges 2011).

Walking is an essential element in everyday activities, and constitutes a major component in current physical activity guidelines for patients with LBP (Simmonds and Derghazarian 2009). Compared to asymptomatic individuals, patients with cLBP spontaneously adopt a decreased walking speed (Lamoth et al. 2008; Simmonds et al. 2012; Lee et al. 2007). More specifically, several biomechanical changes have been reported. Lamoth et al. (2006b) observed a decreased variability in the coordination between trunk and pelvic rotations in the transverse plane, but an increased variability in the frontal plane. The same group reported a decreased ability of patients to adapt trunk–pelvis coordination to changes in velocity (Lamoth et al. 2006a), which was aggravated under the influence of an attention-demanding task (Lamoth et al. 2008), suggesting a stronger cognitive regulation of gait. From the study of Crosbie et al. (2013), it appears that alterations in spinal movement and coordination persist, yet in a small extent, in patients with recurrent low back pain who are pain free at the time of testing. These adaptations have been suggested to result from increased trunk stiffness as a protective strategy to prevent further injury or pain (van den Hoorn et al. 2012).

Muscle activation patterns confirm the hypothesis of a guarding mechanism during walking in patients with cLBP. Increased lumbar muscle activation has been reported during the total stride (van der Hulst et al. 2010b; Vogt et al. 2003), including both swing (Lamoth et al. 2006b; van der Hulst et al. 2010b) and double support periods (van der Hulst et al. 2010b). Cocontraction of the erector spinae and rectus abdominis is also increased in patients with cLBP compared to asymptomatic controls (van der Hulst et al. 2010a). In healthy participants, experimentally induced pain or fear of pain during walking had only subtle effects on trunk coordination and erector spinae activity, suggesting that the aforementioned adaptations are long-term rather than short-term consequences of pain (Lamoth et al. 2004).

In normal subjects, walking is characterized by exchanges between potential and kinetic energy, as illustrated by the inverted pendulum model developed by Cavagna et al. (1976) This transfer of energy minimizes the work to be produced by muscles, and hence the energy cost of walking. In several pathologic conditions, gait pattern alterations are associated with an increased energetic cost of walking (Mahaudens et al. 2009; Bernardi et al. 1999). In patients with cLBP, the aforementioned adaptations (altered trunk–pelvis coordination, increased muscle activation and stronger cognitive regulation of gait) may also cause an augmented production of mechanical work and an increased metabolic demand. To our knowledge, no study has been undertaken on this issue.

The present study aimed to compare the preferred walking speed, the biomechanical and the energetic parameters of walking at different speeds between patients with cLBP and healthy men. It was hypothesized that the preferred walking speed would be lower, and that the mechanical and metabolic demand at fixed/standard speed of walking would be higher in patients with cLBP compared to healthy participants.

Methods

Participants

The present study included 13 men with cLBP (cLBP group) recruited among patients on the waiting list for functional multidisciplinary rehabilitation at the Service of Rheumatology of Lausanne University Hospital (Switzerland). Thirteen healthy control men (CTR group) were recruited through posted announcements, and individually matched to patients for age, body mass and height. For patients, inclusion criteria were age between 30 and 60 years and non-specific low back pain for at least 12 weeks. Exclusion criteria were irritative neurological deficit in progress, sciatica, acute inflammatory rheumatic disease, non-osteoarticular thoracic pain, spinal fracture within the last 3 months, osteoporosis, tumour, severe heart failure or respiratory failure, obesity (body mass index >30), entitled to a total disability pension, active drug addiction, current involvement in litigation related to low back pain, and active psychiatric pathology.

Participant recruitment and data collection were conducted from July to November 2011. Each participant was informed in detail about the study, and provided written consent. They received a financial compensation of CHF 50. Lausanne University Medical School's Clinical Research Ethics Committee approved the study.

Experimental design

Participants attended a single 2-h testing session. After 10 min of treadmill accommodation across experimental walking speeds and a brief rest period, the preferred walking speed was determined. Anthropometric measurements were then taken and subjects were asked to complete some questionnaires. Successively, participants were equipped with a breath-by-breath gas analyser and two inertial sensors fitted with a triaxial accelerometer and gyroscope and the treadmill protocol started.

Preferred Walking Speed (PWS)

After treadmill familiarization across experimental walking speeds (0.83, 1.11, 1.38, 1.67 m s^{-1}) and a brief rest period, each subject's PWS was determined according to the methodology proposed by Martin et al. (1992) Briefly, each subject began treadmill walking at the lowest experimental speed (0.83 m s^{-1}), which was then slowly increased until the subject subjectively identified his PWS. This speed was maintained for a minute and was then eventually slightly modified according to subject directives. This procedure was repeated starting with the highest experimental speed (1.67 m s^{-1}) and gradually reducing to the preferred speed. The final PWS was considered to be the mean of the two speeds selected by the subject during both the increasing and decreasing speed trials.

Treadmill protocol

The treadmill protocol was determined according to the procedure proposed by Malatesta et al. (2003) After a 4-min measure of the standing rate of oxygen consumption, participants were asked to complete 5-min walking trials at five different speeds (0.83, 1.11, 1.38, 1.67 m s^{-1} and PWS) in randomized order, separated by 5-min resting periods. Participants were instructed to walk as naturally as possible in the middle of the belt and without using handrail support.

Assessments

Anthropometric measurements

Each subject was weighed with a standard balance. Stature was measured to the nearest 0.5 cm using a standardized wall-mounted height board, and body mass index (BMI) was calculated as body mass divided by height squared. The leg length was determined with the subject in standing position as the distance between the great trochanter and the ground for the left leg.

Questionnaires

The physical activity level of each participant was estimated using the short form of the International Physical Activity Questionnaire (IPAQ) (Gauthier et al. 2009), which covers activities performed at work, at home, when on the move and during leisure time. Algorithms that take into account the frequency, volume and intensity of the reported physical activities classify participants as 'high', 'moderate' or 'low' physical activity level. The disability level of cLBP group participants was measured with the Oswestry Disability Index (ODI), validated French version (Vogler et al. 2008). This 10-item scale provides a score ranging from 0 to 100 %. A high score indicates a high degree of disability. A value of 12 was reported as a cut-off which separates cLBP patients with vs without disability (Tonosu et al. 2012). Fear of movement was assessed in cLBP participants using the Tampa scale for kinesiophobia (TSK), a 17-item scale answered using a 4-point Likert scale (from 'strongly disagree' to 'strongly agree') (Miller et al. 1991). A total score ranging from 17 to 68 was calculated after inversion of the scores on items 4, 8, 12 and 16. A high score indicates a high degree of fear of movement. A value over 37 has been reported to differentiate low-fear and high-fear subjects (Vlaeyen et al. 1995).

Pain and perceived exertion

Low back pain intensity for the cLBP group was measured with a visual analogue scale (VAS) (Price et al. 1983), before the treadmill protocol, after each walking trial and at the end of the treadmill protocol. The Borg scale was used to evaluate the perceived exertion after each walking trial and at the end of the protocol for both cLBP and CTR group participants (Borg 1982).

Sitting and standing oxygen consumption

Oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and ventilation were measured using a breath-by-breath gas analyser (Metalyzer, Cortex Medical, Leipzig, Germany). The calibration of the Metalizer (pressure, volume and standard gases) was realized before each session. Sitting $\dot{V}O_2$ and $\dot{V}CO_2$ were measured during 10 min at a steady state, after the participant had maintained a sitting position for 20 min. Standing $\dot{V}O_2$ and $\dot{V}CO_2$ were measured for 4 min at the beginning of the treadmill protocol. Average $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated over the last minute. Metabolic rate (W kg^{-1}) was calculated based on the energetic equivalent of O_2 (Åstrand and Rodahl 1986).

Energetics of walking and heart rate

Average $\dot{V}O_2$, $\dot{V}CO_2$ and heart rate (HR; Polar S810, Kempele, Finland) were calculated over the last minute of each 5-min walking trial. Gross metabolic rate (W kg^{-1}) for each speed was calculated based on the energetic equivalent of O_2 (Åstrand and Rodahl 1986). Gross energy cost of walking (gross C_w, J kg^{-1} m^{-1}) was then calculated as the gross metabolic rate (W kg^{-1}) divided by the walking speed. A second-order least squares regression was used to model the U-shaped relationship between gross C_w and walking speed and calculate the optimal walking speed (OWS: the most economical speed) for each subject. Net energy cost of walking (net C_w, J kg^{-1} m^{-1}) was calculated by subtracting standing metabolic rate (W kg^{-1}) from gross metabolic rate and dividing by the walking speed.

Mechanics of walking

Two inertial sensors equipped with a triaxial accelerometer and gyroscope (MTx, Xsens, Enschede, The Netherlands) were used to calculate the three-dimensional accelerations of walking as previously described by Peyrot et al. (2009). An inertial/gyroscope sensor was taped and secured directly to the skin on the lower part of the back, at the L3 level (close to the centre of body mass, COM) using an adhesive strap. This sensor was used to measure the COM accelerations, under the assumption that changes in the relative positions of the sensor and COM over walking time may be neglected. Then, a second sensor was also taped and secured on the instep of subjects' left foot to detect foot events.

Data were processed according to the methodology previously described by Peyrot et al. (2009) Briefly, the inertial sensors provided orientation data in the earth reference system in the form of Euler angles (roll, pitch and heading), which represent rotations of the sensor system into the earth reference system. Since the magnetic north corresponded to the anteroposterior axis in the present study, the three-dimensional accelerations of the two sensors were repositioned in the earth reference system using rotation matrices. All data were sampled at 100 Hz and low-pass filtered at 30 Hz (fourth-order, zero-lag, low-pass Butterworth).

Spatiotemporal parameters

Foot angular velocities were used to determine heel strike and toe-off (Jasiewicz et al. 2006). Stride duration, stance duration and single support duration of the contralateral limb were computed as heel strike to consecutive heel strike, heel strike to consecutive toe-off, and toe-off to consecutive heel strike, respectively. Stance and single support durations were expressed relatively to stride duration (%). Stride frequency (Hz) was calculated as the inverse of stride duration. Stride length (m) was calculated by multiplying walking speed and by stride duration.

Mechanical work

Mechanical analyses were performed over ten consecutive strides taken during the last minute of each walking trial. A stride was defined as the period between two consecutive left heels. Mechanical parameters were computed for each stride and then averaged to describe a mean typical stride. According to Cavagna et al. (1976), vertical, forward and medio-lateral (M-L) COM velocities and positions were obtained by integrating twice the three-dimensional accelerations of the mean stride.

The total instantaneous potential (E_p; J) and kinetic (E_k; J) energies of the COM were calculated as follows:

$$E_p = m \times g \times h \tag{1}$$

$$E_k = E_{kf} + E_{kv} + E_{kl} = 0.5 \times m \times \left[(V_x)^2 + \left(V_y\right)^2 + (V_z)^2\right] \tag{2}$$

where m is the body mass (kg); g is the gravitational constant; h is the vertical position of the COM; E_{kf}, E_{kv} and E_{kl} are the forward, vertical and lateral kinetic energies, respectively; and V_x, V_y and V_z are the forward, vertical and lateral velocity components (m s^{-1}), respectively. The total mechanical energy of the COM (E_{tot}; J) was calculated as the sum of E_p and E_k and the external mechanical work (W_{ext}; J kg^{-1} m^{-1}) as the sum of the positive increments in E_{tot} divided by stride length and by body mass.

The inverted pendulum recovery of mechanical energy of the COM (Recovery; %) was calculated as follows:

$$\text{Recovery} = \frac{\Delta E_p + \Delta E_k - W_{ext}}{\Delta E_p + \Delta E_k} \times 100 \tag{3}$$

where ΔE_p (J) and ΔE_k (J) are the fluctuations in potential and kinetic energy of the COM.

Mechanical internal work (W_{int}, J kg^{-1} m^{-1}) was calculated with the equation of Nardello et al. (2011) as follows:

$$W_{int} = f \times v \times \left(1 + \left(\frac{d}{1-d}\right)^2\right) \times 0.08 \tag{4}$$

where f is the stride frequency (Hz); v is the walking speed (m s^{-1}); and d is the duty factor. The total mechanical work (W_{tot}, J kg^{-1} m^{-1}) was calculated as the sum of W_{ext} and W_{int}.

Table 1 Participant characteristics

Variable	cLBP ($n = 13$)	CTR ($n = 13$)
Age (years)	44.0 (7.4)	42.4 (9.4)
Body mass (kg)	78.6 (8.9)	77.4 (10.5)
Height (m)	1.74 (0.06)	1.75 (0.07)
Lower limb length (m)	0.96 (0.04)	0.96 (0.05)
BMI (kg m^{-2})	25.9 (2.5)	25.4 (4.3)
IPAQ		
High level	7	4
Moderate level	6	6
Low level	0	3
Occupation		
Manual	5*	2
Non manual	3*	9
Half manual	4*	1
Children		
No child	4	4
1 child	2	2
≥2 children	7	7
Smoking status		
Smoker	5	2
Non smoker	8	11
Origin		
Swiss	5	6
Other	8	7

Mean values (standard deviation)

cLBP chronic low back pain group and *CTR* control group, *n* number of participants, *BMI* body mass index, *IPAQ* International Physical Activity Questionnaire

* Significant difference between cLBP and CTR groups ($P < 0.05$)

Medio-lateral COM displacement

The medio-lateral COM displacement was equal to the total amplitude (from left to right) of the medio-lateral COM position calculated by integration of the medio-lateral velocity.

Statistical analysis

Data are expressed as means (standard deviation) for all variables. The sample size was based on a previous study (Mahaudens et al. 2009) that reported a net C_w of 2.4 (0.4) J kg^{-1} m^{-1} and 1.8 (0.3) J kg^{-1} m^{-1} in adolescents with or without idiopathic scoliosis, respectively. To detect a 0.6 J kg^{-1} m^{-1} difference with a standard deviation of 0.4 J kg^{-1} m^{-1}, 90 % power and at the 5 % significance level, a minimum of 11 participants in both study groups was required. A *t* test was used to test differences between anthropometric characteristics of the two groups. A χ^2 was used to compare the distribution of the two groups in the three physical activity levels of IPAQ. A two-way repeated-measures mixed design ANOVA [walking speed ($n = 4$; 0.83–1.67 m s^{-1}) × group (cLBP vs CTR)] followed by contrasts was used to determine the effect of pathology and speed on energetic and mechanical variables of walking. As it is well established that speed influences these variables, main effects of speed are not reported. A *t* test was used to determine difference in PWS and in energetic and mechanical at PWS between groups. Difference between PWS and OWS for the two groups was tested with a *t* test. The level of significance was set at $P \leq 0.05$. The analyses were conducted using SPSS 21 software (IBM, Armonk, NY).

Results

Participants' characteristics

The characteristics of the study participants are presented in Table 1. There were no significant differences in body mass index ($P = 0.64$), lower limb length ($P = 0.80$) and individuals distribution in the number of children ($P = 1.00$), smoking status ($P = 0.18$), origin ($P = 0.69$) and the three physical activity levels of IPAQ ($P = 0.14$) between the two groups. Patients with cLPB were significantly more often manual workers than CTR participants ($P = 0.05$), which may explain the tendency towards a higher level of physical activity in the cLBP compared to CTR group. For cLPB participants, mean duration of symptoms was 5.6 (7.3) years, ODI and TSK scores were 29.2 (10.2) and 46.8 (6.2), respectively. These values indicate moderate levels of disability and fear of movement. The minimum and maximum ODI scores were, respectively, 14 and 50, indicating that all participants from the cLBP group were above the cut-off value of 12 defining patients with disability. The minimum and maximum TSK scores were, respectively, 36 and 56. A total of 12 patients had a TSK score >37 defining a high fear.

PWS (Table 2) and OWS [cLBP: 1.33 (0.09) m s^{-1} and CTR: 1.41 (0.09) m s^{-1}] were significantly slower in cLBP than in CTR group ($P = 0.002$ and $P = 0.03$, respectively). OWS was significantly higher than PWS in cLBP group ($P = 0.003$), but not in CTR group (Fig. 1; $P = 0.08$).

Rest metabolic rate and energetics of walking

There were no significant differences in sitting [cLBP: 1.18 (0.22) W kg^{-1}; CTR: 1.32 (0.19) W kg^{-1}] and standing [cLBP: 1.38 (0.20) W kg^{-1}; CTR: 1.46 (0.20) W kg^{-1}] metabolic rate between the two groups ($P = 0.09$ and $P = 0.32$, respectively). Gross C_w and net C_w were not significantly different between the two groups at the four standard walking speeds ($P = 0.88$ and $P = 0.36$,

Table 2 Energetic and mechanical variables at preferred walking speed (PWS) for the two groups

Variable	cLBP ($n = 13$)	CTR ($n = 13$)
PWS (m s^{-1})	1.17 (0.13)*	1.33 (0.11)
Energy cost		
Gross C_w (J kg^{-1} m^{-1})	3.22 (0.28)	3.16 (0.36)
Net C_w (J kg^{-1} m^{-1})	2.06 (0.25)	2.07 (0.21)
Spatiotemporal parameters		
Stride frequency (Hz)	0.97 (0.06)*	1.29 (0.15)
Stride length (m)	0.90 (0.04)*	1.06 (0.15)
Medio-lateral displacement (m)	0.05 (0.01)*	0.04 (0.01)
Single support duration (%)	78.2 (2.8)	79.8 (2.5)
Double support duration (%)	21.8 (2.8)	20.2 (2.5)
Mechanical works and recovery		
W_{tot} (J kg^{-1} m^{-1})	0.69 (0.12)*	0.82 (0.11)
W_{ext} (J kg^{-1} m^{-1})	0.40 (0.10)*	0.48 (0.09)
W_{int} (J kg^{-1} m^{-1})	0.29 (0.03)*	0.34 (0.03)
Recovery (%)	64.9 (8.1)	59.2 (6.2)
Heart rate (bpm)	84.7 (11.1)	86.5 (10.3)
Perceived exertion, score	10.6 (1.9)	9.5 (1.4)

Mean values (standard deviation)

cLBP chronic low back pain group and *CTR* control group, *n* number of participants, *Gross* C_w gross energy cost of walking, *Net* C_w net energy cost of walking, W_{tot} total mechanical work, W_{ext} mechanical external work, W_{int} mechanical internal work, *bpm* beats per minute

* Significant difference between cLBP and CTR groups ($P < 0.05$)

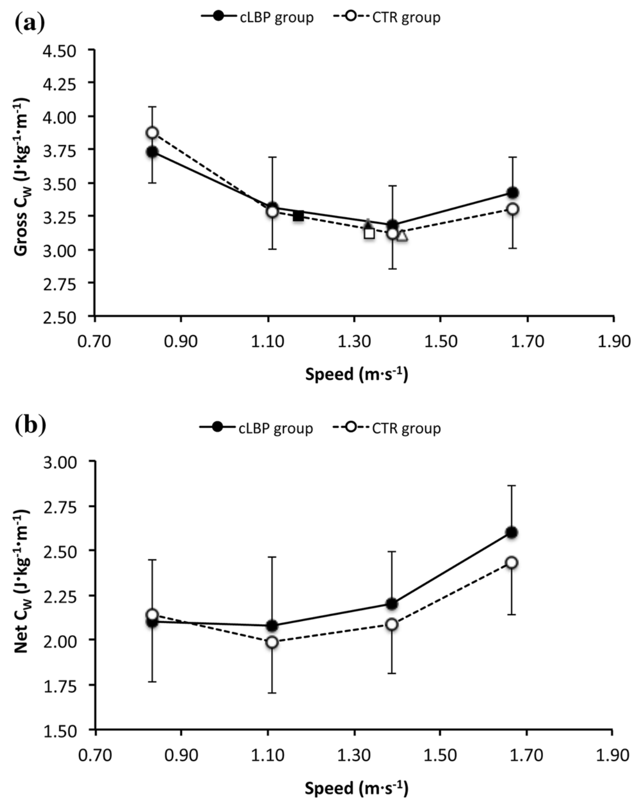

Fig. 1 Energy cost of walking for the two groups at standard walking speeds. **a** gross energy cost of walking (gross C_W); **b** net energy cost of walking (net C_W). *cLBP* chronic low back pain, *CTR* control, *filled square* preferred walking speed (PWS) for cLBP group, *hollow square* PWS for CTR group, *filled triangle* optimal walking speed (OWS) for cLBP group, *hollow triangle* OWS for CTR group. Values are means (standard deviation)

respectively) and at PWS (Fig. 1; Table 2; $P = 0.65$ and $P = 0.88$, respectively). The group × walking speed interactions were not significant ($P \geq 0.05$).

Mechanics of walking

Spatiotemporal parameters

There were no significant differences in stride frequency ($P = 0.91$), stride length ($P = 0.99$) and medio-lateral displacement ($P = 0.16$) at the four fixed walking speeds between the two groups (Fig. 2). In addition, for these speeds, the single and double support stride durations (%) were similar in the two groups (data not shown; $P = 0.80$ for both). At PWS, stride length and frequency were significantly lower ($P = 0.004$ and $P < 0.001$, respectively) and medio-lateral displacement was significantly higher ($P = 0.03$) in cLBP compared with CTR group (Table 2). In contrast, at this speed, there were no significant differences in the single and double support stride durations (%) between the two groups (Table 2; $P = 0.14$ for both). The group × walking speed interactions were not significant ($P \geq 0.11$).

Mechanical works and recovery

W_{tot}, W_{ext}, W_{int} and recovery at the four standard walking speeds were not significantly different between the two groups (Fig. 3; $P \geq 0.44$). At PWS, W_{tot}, W_{ext}, W_{int} were significantly lower in cLBP than in CTR group (Table 2; $P = 0.007$, $P = 0.04$ and $P < 0.001$, respectively). There was no significant difference in recovery at PWS between the two groups (Table 2; $P = 0.06$). The group × walking speed interactions were not significant ($P \geq 0.10$).

Heart rate, pain and perceived exertion

There was no significant difference in HR at the four fixed walking speeds between the two groups (Fig. 4a; $P = 0.58$). Perceived exertion showed a significant main group effect ($P = 0.02$) with Borg scale scores significantly higher at 1.11 and 1.38 m s^{-1} ($P = 0.01$ and $P = 0.02$, respectively) and tends to be higher at 0.83 and

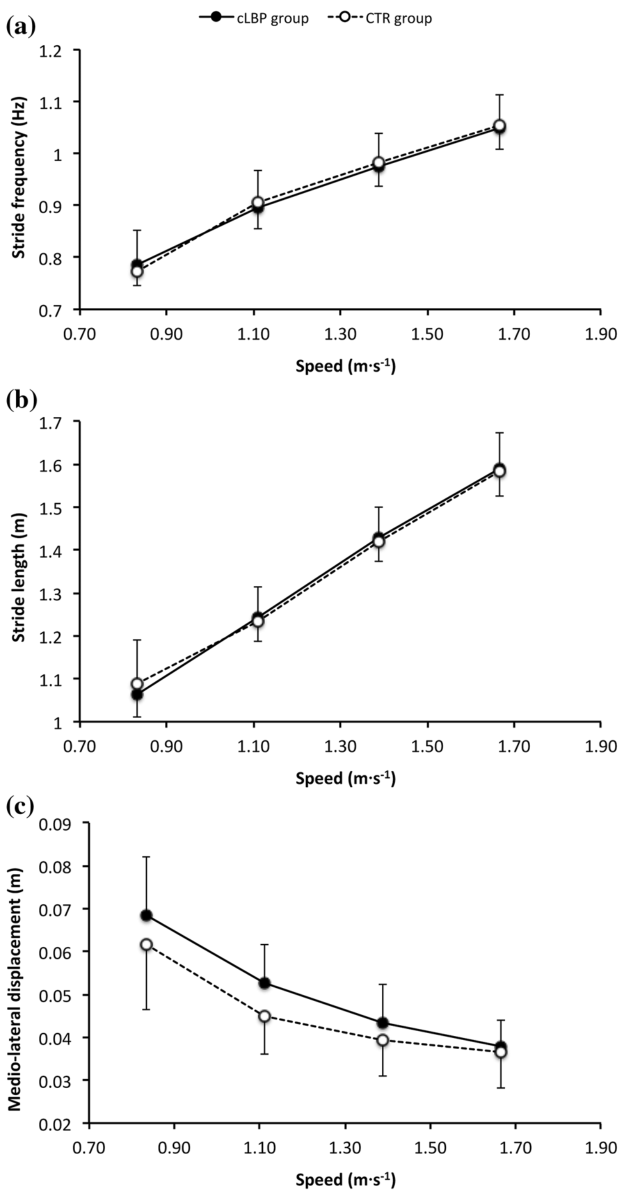

Fig. 2 Spatiotemporal parameters for the two groups at standard walking speeds. **a** stride frequency, **b** stride length, **c** medio-lateral displacement. *cLBP* chronic low back pain, *CTR* control. Values are means (standard deviation)

1.67 m s^{-1} in cLBP compared with CTR group (Fig. 4b; $P = 0.06$ and $P = 0.09$, respectively). For both variables, the group × walking speed interactions were not significant ($P \geq 0.26$). At PWS, perceived exertion and HR were similar in both groups (Table 2; $P = 0.16$ and $P = 0.68$, respectively). At the end of the experimental trail, Borg scale score was significantly higher in cLBP [11.7 (2.4)] than in CTR group [9.9 (1.1); $P = 0.01$]. For cLBP individuals, during experimental session, there was no significant time evolution in low back pain intensity assessed with VAS (Fig. 4c; $P = 0.21$).

Discussion

The aim of this study was to compare the preferred walking speed, the biomechanical and the energetic parameters of walking between patients with cLBP and matched healthy controls. Preferred walking speed was lower in patients with cLBP, but no significant difference was observed between groups in mechanical work, spatiotemporal parameters and energy cost of walking. These results do not support the hypothesis of a less efficient walking pattern in patients with cLBP.

Considering the multiple gait adaptations previously reported in patients with cLBP (i.e. altered trunk–pelvis coordination, increased muscle activation and stronger cognitive regulation of gait) (Vogt et al. 2003; Lamoth et al. 2004, 2006a, b, 2008; van der Hulst et al. 2010a, b, 2012; Crosbie et al. 2013), an augmented production of mechanical work and an increased metabolic demand were expected in patients with cLBP compared to control participants. The absence of any difference in the energetics and mechanics of walking between groups may be explained by several reasons. The aforementioned motor control changes may not be sufficiently large to cause a less efficient walking pattern. In fact, it has previously been shown that the peripheral musculoskeletal disorders, inducing lowest-level gait disturbances, did not affect W_{ext} and R, whereas central nervous system pathologies, causing middle-level gait disorders, altered the mechanics of walking impairing the pendular energy transfer and increasing W_{ext} compared with normal gait (Detrembleur et al. 2000). This suggests that W_{ext} and recovery may be "a sensitive indicator to distinguish between central and peripheral neurological disorders" (Detrembleur et al. 2000). Alternatively, these changes may occur without compromising the walking pattern efficiency, or in conjunction with compensating adaptations as a strategy to maintain the energetic cost of walking at a low level. As previously shown, unilateral amputee patients walk with C_w, W_{ext} and recovery ranging within normal values because they are able to compensate the lower W_{ext} and higher recovery during prosthetic limb step with greater W_{ext} and lower recovery during normal limb step (Tesio et al. 1998). However, with our study design, we cannot determine the potential mechanisms involved in this possible compensation. Thus, future studies, which would include kinematic and EMG data in addition to the parameters already assessed in the present study, are needed to further investigate these potential compensating mechanisms in patients with cLBP.

The lower preferred walking speed in patients with cLBP, and consequently the shorter stride length and lower stride frequency at preferred walking speed, is consistent with previous studies (Lamoth et al. 2008; Simmonds et al. 2012; Lee et al. 2007). These changes are similar to

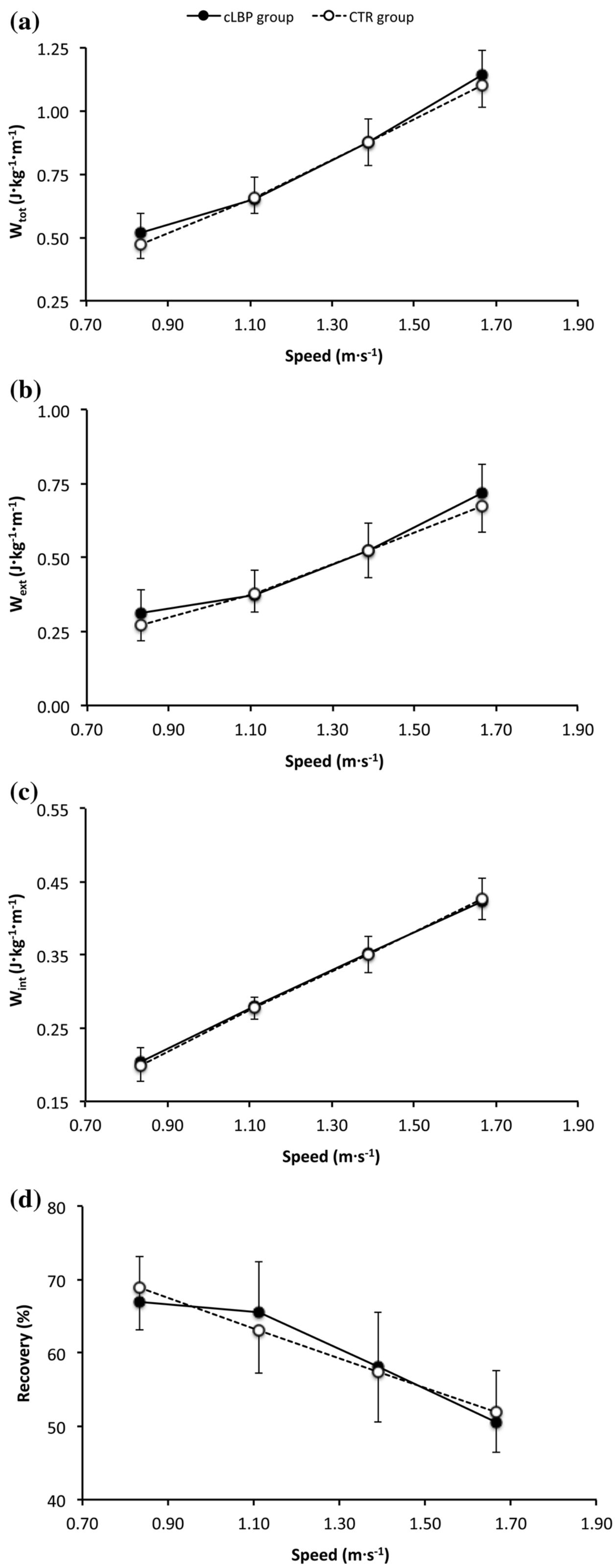

Fig. 3 Mechanical works and recovery for the two groups at standard walking speeds. **a** total mechanical work (W_{tot}), **b** mechanical external work (W_{ext}); **c** mechanical internal work (W_{int}); **d** recovery. *cLBP* chronic low back pain, *CTR* control. Values are means (standard deviation)

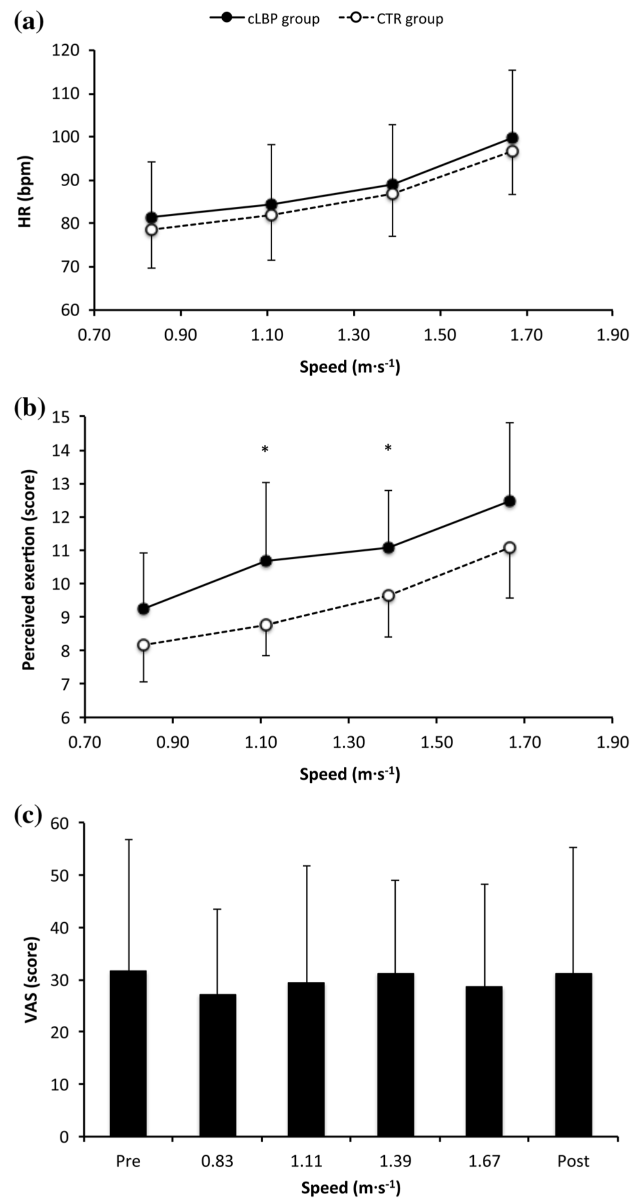

Fig. 4 Heart rate, pain and perceived exertion. **a** heart rate (HR), **b** perceived exertion (Borg scale score) for the two groups; **c** low back pain intensity (visual analogue scale score—VAS) for cLBP group. *cLBP* chronic low back pain, *CTR* control, *bpm* beats per minute. *Significant difference between cLBP and CTR groups ($P < 0.05$). Values are means (standard deviation)

those induced by healthy ageing after age 50 [for review see Beijersbergen et al. (2013)]. After this age, PWS is an indicator of general physical health and predicts daily function, independent living and many other clinical conditions (Beijersbergen et al. 2013). These earlier gait modifications in our younger patients may thus limit the ability to perform everyday tasks and increase sedentary behaviour in this population. Several hypotheses can be put forward to explain lower PWS in patients with cLBP. First, it may result from a strategy aiming to limit pelvic and thoracic rotations and decrease the expected loads on spinal tissues. In healthy individuals, pelvic and thoracic transverse rotations typically evolve from in-phase (pelvis and thorax move in the same direction) towards antiphase rotations (pelvis and thorax move in opposite directions) as walking speed increases (Lamoth et al. 2002). Patients with cLBP exhibit less antiphase coordination (Lamoth et al. 2002; 2006b), which may explain why they prefer lower walking speeds. Second, a lower walking speed may be used to cope with postural instability. Given the decreased ability of patients with cLBP to provide adequate spinal stability (Panjabi 2003), walking slowly may allow them to adapt to unexpected perturbations during walking with a greater margin of safety (Taylor et al. 2003). Besides, at PWS, the medio-lateral displacements of COM were higher in cLBP than in control group (+20 %). This is indirect evidence that cLBP patient takes wider steps as compared to control individuals and may represent an active strategy to increase dynamic balance during walking as previously shown in pathological gait (Kuo and Donelan 2010). Third, patients may spontaneously adopt a decreased speed to set intensity at a lower percentage of their maximal aerobic capacity and thus decrease the physiological relative effort at PWS. However, this would be an inefficient strategy since the energetic cost of walking was minimal at a speed (OWS) that was higher than their preferred walking speed. Finally, fear of pain is an important factor in the development and persistence of cLBP (Vlaeyen and Linton 2012). The belief that pain would be exacerbated if walking speed gets higher may have rendered patients comfortable at a lower speed. In a preliminary analysis of the present data, there was no significant correlation between PWS and the TSK score (Pearson $r = -0.136$; $P = 0.66$). This association was also not significant in the study of Lamoth et al. (2006b). However, the number of participants in both studies precludes from drawing firm conclusions.

Patients with cLBP did not report higher levels of pain at fast compared to low speeds. Similarly, Lamoth et al. (2006b) did not find a significant increase in pain intensity before and after a walking protocol. A decrease in pain intensity was even reported by other authors in patients with recurrent LBP (Lee et al. 2007). In the present study, whereas pain VAS remained around 30 at all walking speeds, the task was perceived as more difficult by patients with cLBP than controls, as indicated by a higher level of perceived exertion, but this difference was not intensified with increasing speed. In a previous study, a back fatiguing task was subjectively perceived as more strenuous by patients with cLBP than healthy controls, whereas objective EMG recordings showed no significant difference between groups (Lariviere et al. 2010). Ratings of perceived exertion may be influenced by factors such as pain and fear of movement (Barker et al. 2003; Wallbom et al. 2002).

A major strength of the present study is that matching between patients and controls prevented from a confounding effect of age, body mass and height on energetics and mechanics of walking. Some limitations must, however, be mentioned. First, only males were included to limit the required sample size and to avoid an effect of sex on the results. It has been shown that the energy cost of walking is 10 % higher in females than males (Browning et al. 2006). The present findings must therefore be interpreted with caution in females. However, considering the very small differences observed between groups in mechanical work, spatiotemporal parameters and energy cost of walking, and under the assumption that sex accounts for a different energy cost of walking in both patients with chronic LBP and healthy individuals, the probability that different conclusions would be drawn in females appears to be small. Second, a wide range of walking speeds was required to model the U-shaped relationship between gross C_w and walking speed and to calculate OWS, which precluded from recruiting highly disabled patients. Although the study sample is representative of the target population in terms of duration of symptoms, pain severity and fear of movement, the results cannot be generalized to highly disabled patients, which represent 15–20 % of patients with cLBP (Payares et al. 2011; Osthus et al. 2006). Third, although inertial sensors are sufficiently accurate to measure the mechanics and the spatiotemporal parameters of walking (Meichtry et al. 2007; Peyrot et al. 2009), approximations may have arisen from skin movements or changes in the relative positions of the sensor and COM over walking time. Although these factors cause an overestimation of the mechanical work and power (Meichtry et al. 2007), such errors cannot have substantially affected the comparisons between patients with chronic LBP and controls because the same methodology was used in both groups.

In conclusion, patients with cLBP have a lower preferred walking speed than matched control participants, but no significant difference in mechanical work and energy cost of walking was observed between groups. These findings do not argue in favour of prescribing training modalities aimed at improving gait efficiency. At the same time, an increase in energy cost of walking does not appear to be a factor that discourages patients from engaging in physical activity. The moderate levels of perceived exertion, and the absence of pain exacerbation over the study protocol, imply that high walking speeds are well tolerated by patients with moderately disabling cLBP, and may be used effectively to increase the preferred walking speed, and to improve aerobic capacity in deconditioned patients.

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Compliance with the ethical standards

Conflicts of interest The authors have nothing to disclose.

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