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A comparison of standing postural control and gait parameters in people with and without chronic low back pain. A cross-sectional case-control study.

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ABSTRACT

Objective

Differences in postural control and gait have been identified between people with and without chronic low back pain (CLBP), however many previous studies present data from small samples, or have utilised methodologies with questionable reliability. This study, employing robust methodology, hypothesised that there would be a difference in postural control, and spatiotemporal parameters of gait in people with CLBP compared to asymptomatic individuals.

Methods

This cross-sectional case-control study age- and gender-matched 16 CLBP and 16 asymptomatic participants. Participants were assessed barefoot i)standing, over three 40 second trials, under four posture challenging conditions ii)during gait. Primary outcome was postural stability (assessed by root mean squared error of centre of pressure (CoP) displacement (CoP_{RMSEAP}) and mean CoP velocity (CoP_{VELAP}), both in the antero-posterior direction); gait outcomes were hip range of movement and peak moments, walking speed, cadence, and stride length, assessed using force plates and a motion analysis system.

Results

There were no differences between groups in CoP_{RMSEAP}($p=0.26$), or CoP_{VELAP}($p=0.60$) for any standing condition. During gait, no differences were observed between groups for spatio-temporal parameters, maximum, minimum and total ranges of hip movement, or peak hip flexor or extensor moments in the sagittal plane.

Conclusions

In contrast to previous research, this study suggests that people with mild to moderate CLBP present with similar standing postural control, and parameters of gait to asymptomatic individuals.

Treatments directed at influencing postural stability (for example, standing on a wobble board) or specific parameters of gait may be an unnecessary addition to a treatment programme.

INTRODUCTION

Differences in postural control[1-4] and gait[5-10] have been identified between people with and without chronic low back pain (CLBP). During more challenging standing conditions people with CLBP have demonstrated increased centre of pressure (CoP) displacements and velocities,[1-4] indicative of poorer postural stability.[11-12] A systematic review investigating difference in standing postural sway between those with and without CLBP reports inconsistent findings.[13] Although, the majority of studies reported an increased postural sway in people with LBP, evidence from fewer studies, many with larger sample sizes and more robust methodologies demonstrated no difference between groups.[13] Hence, whether a true difference exists remains unclear.

During gait, people with CLBP have demonstrated reduced self-selected walking speed,[5-8] stride time,[9-10] stride length[5-6] and range of hip movement[9] compared to people without back pain. Due to the proposed decrease in stride length, walking speed and hip range of movement, hip joint moments are also likely to be decreased in people with CLBP compared to people without.[14] Researchers have proposed that such gait changes may be an attempt by the individual to reduce pain by reducing: ground reaction forces at heel strike;[15] excessive muscle activity; or joint movement.[16] Alternatively, differences may be a result of altered proprioceptive feedback[17] or psychological factors associated with CLBP, such as anxiety, fear avoidance and catastrophising.[18] Psychological factors may lead to adaptation of normal physical activities, such as fast walking, due to the fear of increasing pain. Although gait alterations may initially be protective, such alterations may induce mechanical problems in the long-term, for example, a slower walking produces longer periods of loading on the lumbar spine during gait,[19] which may be detrimental to spinal

structures in the long-term, whereas shorter periods of loading, thought to be less detrimental, occur during faster walking.[19]

These differences in postural control[1-4] and gait[5-10] have been proposed as contributing factors to the presence and recurrent nature of CLBP[1,4,15] However, previous studies have used: small sample sizes[2-3] (possibly introducing a type 2 error); methodological design likely to result in low reliability of data, e.g. analysing data from one trial instead of multiple trials;[1,5,8,9] outcomes that have demonstrated poor reliability; or provide results not representative of the general population (for example: all or mainly male participants;[8-9] or walking on a treadmill as opposed to on normal ground[7,9,10]).

This study aimed to add to current research by utilising a more reliable and valid methodology to determine whether participants with CLBP have similar or different barefoot standing postural control, and gait parameters, when compared with age- and gender-matched asymptomatic participants. The following hypotheses were investigated:

H_1: The CLBP group will demonstrate greater postural instability when compared to the asymptomatic group during more challenging standing conditions.

H_2: Reduced self-selected walking speed, cadence and step length will be observed in people with CLBP compared to asymptomatic individuals.

H_3: During gait, people with CLBP will present with reduced peak hip extensor moments during stance phase and reduced hip range of movement compared to asymptomatic individuals.

METHODS

This cross-sectional case-control study compared barefoot standing balance and gait data from CLBP participants with that from age- and gender-matched asymptomatic participants.

Ethical approval

Ethical approval for the recruitment of symptomatic (Outer North London Research Ethics Committee' [REC: 10/H0724/7]) and asymptomatic participants (King's College London Research Ethics Subcommittee [BDM/10/11-7]) was gained.

Participant recruitment

A convenience sample of asymptomatic adults was recruited from acquaintances and colleagues of the investigators. Participants with CLBP were recruited from four Physiotherapy Departments in London (United Kingdom) (three National Health Service Hospitals, one private Physiotherapy Practice) following clinical referral from General Practitioners and Consultants as part of a previously reported randomised control trial (RCT).[20] During the second half of the recruitment period of the RCT, 55 participants were asked to participate in the current study, 38 of which showed interest. 18 participants could not attend the session in the main due to work commitments. Of the remaining 20 only 16 participants could be matched by age and gender to our asymptomatic group. Inclusion criteria for symptomatic individuals were: aged 18 to 65 years, with a three month or greater history of LBP. Exclusion criteria were constant non-mechanical LBP, lumbar radiculopathy, known spondylolysthesis, spinal stenosis or inflammatory back pain, specific spinal diagnosis inappropriate for physiotherapy interventions (for example spinal fracture or infection); any condition inappropriate for exercise physiotherapy (for example severe cardiovascular or metabolic disease) or for wearing rocker-sole footwear (for example Morton's neuroma, peripheral neuropathy). Potential asymptomatic participants were contacted via email including the Participant Information Sheet, and were asked to contact CSM if they wished to partake in the study. Asymptomatic participants reported no history of LBP in the last year, were required to meet all other inclusion and exclusion criteria presented above. As increasing age is a contributing factor to poorer postural stability[21] and gender may influence postural control,[22] hence potential confounding factors, asymptomatic participants were matched by age and gender to symptomatic participants. An age range of two

years above or below the age of the 'matched' CLBP participant was classed as acceptable. Sixteen asymptomatic participants were consented into the study.

Data Collection.

Data collection occurred at the 'One Small Step Gait Laboratory', Guys' Hospital, London. Demographic and pain scores (numerical rating scale) representing their level of back pain on the day of assessment were recorded from all participants.

Biomechanical assessment

Participants were assessed wearing short trousers and vest or no top. Participants' anthropometric measurements (pelvic width; leg length; knee width; ankle width; height; and weight) were recorded to inform the mechanical model formulated for each participant in Vicon's Nexus (1.8.1) motion capture software (Vicon Motions Systems, Oxford, UK). The motion analysis system consisted of seven cameras, capturing retro-reflective markers in three-dimensional space at a rate of 120 Hertz.

Seventeen infra-red reflective markers (14mm diameter) were positioned on each participant by an experienced researcher (AS).[23-25] The Modified Helen Hayes marker set was implemented[26] with additional markers on bilateral iliac crests, and posterior calcanei (Figure 1.).

Postural stability in standing

Participants were assessed barefoot, feet approximately pelvis width apart and on adjacent force plates (FP5000, AMTI Inc., Massachusetts, USA), during four posture challenging standing conditions involving manipulation of visual input and support surface: (1)firm surface, eyes-open; (2)firm surface, eyes-closed; (3)compliant surface, eyes-open; (4)compliant surface, eyes-closed. Compliant

surface was achieved by placing an AirexTM cushion (48.5x40.0x6.4cm, 0.7kg, density 38.6kg/m-3, closed-cell foam) (l-group, St. Louis, MO) over each force plate (Figure 1.).

Participants were instructed to keep their eyes focused on a red sticker at eye height on a tripod three metres in front of them.[27] Participants were assessed for three 40 second trials (shown to produce acceptable reliability[28]) for each standing condition. The middle 30 seconds of each trial was analysed to avoid possible initial sway errors, effects of participant fatigue or anticipation of a trial ending. Each participant received the same instructions at the start of each trial:

"When I say 'Go' I want you to stand and maintain your balance until you hear the instruction to rest. Each trial will last for 40 seconds. Focus on the red sticker on the tripod ahead of you. Keep your arms relaxed by your sides."

A rest period of 20 seconds occurred between each trial. Sufficient trials were performed to provide three valid sets of data. A test was invalidated if the participant moved their foot position during the test, changed their arm starting position, or opened their eyes during an eyes-closed task.

Assessment of gait

Participants were asked to walk barefoot, at a pace that felt comfortable to them, from one end of the laboratory to the other, in a line which passed over three force plates. Each participant received the same instructions:

"When I say go I want you to walk in a straight line to the marker at the other end of the room. Walk at a pace that feels comfortable to you."

Participants continued walking the length of the laboratory until SM had observed three clear force plate strikes (heel-strike and toe-off occurring with the foot making contact with one plate only,

without contacting the plate with the contralateral foot) for each foot. The biomechanical assessment lasted approximately 30 minutes.

Outcome measures

The following postural stability primary outcomes were assessed during standing i) root mean squared error and ii) velocity of the CoP in the antero-posterior direction (CoP_{RMSEAP} and CoP_{VELAP} respectively, Appendix 1). Centre of pressure is a term that refers to the mean position of the forces acting under the feet at any instant in time. The root mean squared error (or standard deviation) of the CoP position reflects the spread of these measurements over a particular time interval (in this case 30 seconds). The velocity of the centre of pressure (CoP_{VELAP}) refers to the mean displacement of the centre of pressure in the anterior-posterior direction, divided by the sample time (1/1080 seconds) over the course of the 30 second trial. Reliability of COP_{VEL} has been reported as excellent (ICC 0.8-0.95) and COP_{RMSE} reported as fair to good (ICC 0.32-0.58) for studies employing similar number of trials and trial durations as the current study.[12]

The following outcome measures were assessed during gait: self-selected walking speed, stride length, cadence, maximum, minimum and total hip range of movement, peak hip flexor and extensor moments.

Data extraction

Force plate data (forces and moments) captured at 1080 Hz and filtered with a low pass Woltering filter (mean standard error $10mm^2$) were exported into Vicon's Nexus software (1.8.1) to calculate biomechanical outcome measures.

Industry-standard motion capture files (.c3d) containing force data were extracted. Force plate data was filtered with a low pass (10Hz) Butterworth filter. CoP parameters were calculated using a proprietary program written in Visual Basic for Applications (Microsoft Excel, Reading, UK).

Sample size

A sample size calculation was not conducted due to the lack of reported data of minimal clinically important difference for the primary outcome measures (CoP parameters). This study aimed to recruit 20 asymptomatic participants age- and gender-matched to symptomatic participants recruited by the authors in a previous RCT.[20]

Data analysis

Independent t-tests for parametric, or Mann-Whitney U-tests for non-parametric data, were applied to determine differences between groups for demographic data and gait outcomes. A mixed-repeated measures ANOVA with two within-subject factors each with two levels - vision (eyes-open and eyes-closed) and support surface (firm and compliant) - determined possible significant main effects and interactions of the two groups for CoP variables. The alpha level for determining statistical significance was set at 0.05. Data were analysed using IBM SPSS 20.0.0 (IBM, New York). Results are presented as means (standard deviations (SD)) unless otherwise stated.

RESULTS

Recruitment and retention

During the recruitment period (June 2010-November 2011) sixteen asymptomatic participants were age- and gender-matched with 16 CLBP participants. The recruitment of matched asymptomatic participants, over the age of 50 years, who had not experienced LBP over the past twelve months proved difficult. This prevented recruitment of the planned sample size of 20 participants per group. There was 100% retention with all 32 participants completing the data collection process.

Baseline characteristics of participants

Demographic characteristics of CLBP and asymptomatic individuals are presented in Table 1. No differences were observed between groups other than self-reported pain scores. Participants with

CLBP reported mild to moderate pain with a Numerical Rating Score range of 3-8, and a mean duration of symptoms of 6.17 (SD 7.59, range 0.25-31) years.

Table 1: Demographic data for chronic low back pain and asymptomatic participants

	Asymptomatic participants (n=16)	Low back pain participants (n=16)	P-value
Gender : Male	8 (50.0%)*	8 (50.0%)*	1.00†
: Female	8 (50.0%)*	8 (50.0%)*	
Age (years)	37.3 (11.1)	36.8 (10.1)	0.90
Weight (kg)	76.3 (13.6)	73.4 (10.6)	0.52
Height (cm)	173.4 (9.3)	173.4 (8.9)	1.00
Numerical rating score for pain (0-10; 0=best)	0.0 (0.0)	5.9 (1.5)	0.00

Summary measures represent means (SD) or *numbers (percentages). †Chi squared test, otherwise independent t-test.

Centre of pressure parameters during standing

Table 2 presents data the antero-posterior centre of pressure parameter data for chronic low back pain and asymptomatic participants during different standing conditions. There were no differences between the groups in $CoP_{RMSE\ AP}$, or $CoP_{VEL\ AP}$ for any of the four standing conditions ($F[2.35, 70.38]=1.39$, $p=0.26$, $\eta^2=0.04$; $F[1.76,52.87]=0.47$, $p=0.60$, $\eta^2=0.02$ respectively).

Table 2. Antero-posterior centre of pressure parameters for chronic low back pain and asymptomatic participants during different standing conditions

		$CoP_{RMSE\ AP}$ [mm]	$CoP_{VEL\ AP}$ [mm/s]
Eyes open, firm surface	Asymptomatic	3.76 (0.84)	6.57 (1.09)
	Chronic low back pain	4.21 (1.88)	7.14 (1.52)
Eyes closed, firm surface	Asymptomatic	3.93 (1.47)	7.14 (1.10)
	Chronic low back pain	4.23 (1.38)	7.39 (1.24)
Eyes open, compliant surface	Asymptomatic	8.29 (1.70)	10.97 (1.78)
	Chronic low back pain	9.10 (2.95)	12.57 (3.96)
Eyes closed, complaint surface	Asymptomatic	8.93 (1.45)	17.15 (4.29)
	Chronic low back pain	10.56 (2.85)	17.98 (4.38)

Summary measures represent means (standard deviation (SD)). (RMSE: root-mean squared error; AP: antero-posterior; VEL: velocity)

Spatio-temporal parameters of gait

No differences were observed between groups for any of the spatio-temporal gait parameters assessed (Table 3).

Table 3 Spatio-temporal parameters of gait in chronic low back pain and asymptomatic individuals

	Asymptomatic group	Chronic low back pain group	P-value
Walking speed [m/s]	1.32 (0.13)	1.25 (0.20)	0.26
Cadence [steps per minute]	115.14 (6.59)	112.43 (11.81)	0.42
Stride length [m]	1.38 (0.12)	1.33 (0.13)	0.33

Summary measures represent means (SD); m: meters; s: seconds. Analysis by independent t-test.

Hip moments and range of movement during gait

No differences were detected between groups for maximum, minimum and total ranges of movement at the hip in the sagittal plane during gait (Table 4). No differences were observed between groups for peak hip flexor or extensor moments during gait (Table 4).

Table 4. Sagittal plane hip range of movement and peak hip joint moments during gait in people with chronic low back pain and asymptomatic individuals

	Asymptomatic	Chronic low back pain	P-value
Left maximum hip flexion [degs]	34.35 (5.55)	33.70 (8.55)	0.78
Right maximum hip flexion [degs]	34.46 (4.51)	33.82 (9.17)	0.79
Left maximum hip extension [degs]	-9.71 (7.39)	-10.44 (9.02)	0.80
Right maximum hip extension [degs]	-9.40 (6.67)	-9.12 (8.74)	0.92
Left hip range of movement [degs]	44.07 (3.94)	44.14 (4.79)	0.97
Left hip extensor moment [Nmm/kg]	1029.30 (329.38)	955.80 (429.78)	0.58
Right hip extensor moment [Nmm/kg]	960.99 (235.24)	1029.57 (460.62)	0.94§
Left hip flexor moment [Nmm/kg]	-990.76 (184.25)	-1098.07 (231.85)	0.14
Right hip flexor moment [Nmm/kg]	-1041.87 (174.80)	-977.77 (194.64)	0.31

Summary measures represent means (SD); degs: degrees; Nmm/kg: Newton-millimeter/kilogram; § represents Mann-Whitney test for non-parametric data, otherwise Independent t-test conducted.

DISCUSSION

In contrast to much other research, the current findings suggest that postural control during standing, and the kinetics, kinematics, and spatio-temporal parameters of gait do not differ between people with CLBP of a mild to moderate intensity and asymptomatic individuals. There were no differences between people with and without CLBP in postural stability during all standing conditions assessed. During barefoot gait, both groups presented with similar peak hip moments and ranges of movement, and spatio-temporal parameters of gait. Hence, all stated hypotheses are rejected.

Centre of pressure parameters

There was no difference in postural stability between CLBP and asymptomatic individuals during stable and more challenging standing conditions. These findings differ from previous research[1-4] possibly due to methodological variation. Della Volpe et al.[2] assessed a smaller sample (n=12 per group) with an 'instrumented platform system', constructed of a moveable support surface and moveable visual surround likely to present participants with a greater postural challenge. This may contribute to the reduced postural stability observed in the CLBP group in their study.[2] Brumagne et al.[1] assessed a larger sample size than the current study (n=45), however, trials were only repeated once – the current study averaged three trials per standing condition, likely to increase reliability of data. [11] Although Brumagne et al.[1] reported reduced postural stability in the CLBP group during more challenging standing conditions, the between-group difference in $CoP_{RMSE\ AP}$ was 1.8mm, and the p-value, 0.046 – bordering on non-significance. In the current study the non-significant difference in $CoP_{RMSE\ AP}$ between the symptomatic and asymptomatic groups during the most challenging postural condition was 1.76mm. Although Brumagne et al.[1] demonstrated statistical significance, based on the very similar yet non-significant between group difference in CoP displacement found in the current study (and in the absence of knowledge regarding cause or effect) it seems unlikely that such a minimal difference in $CoP_{RMSE\ AP}$ is responsible for the clinical differences

in pain and disability observed between the two groups. Mientjes and Frank[3] assessed a small sample (n=8 per group) and although reported significant differences between CLBP and asymptomatic groups during challenged standing conditions, these differences were small (less than 2mm) and similar to those of both the current study and Brumagne et al.[1] Furthermore, Mientjes and Frank[3] report a mean pain score of 0.5 in the 'asymptomatic' group raising concerns that the asymptomatic data may not be a true representation of a pain free population.

The CoP parameters assessed in a research study may influence the reliability of results. CoP velocity consistently demonstrates the best overall reproducibility of all CoP parameters in the short and long term[12,29], hence, findings from this parameter are likely to provide more reliable conclusions to those gained from $CoP_{RMSE\ AP}$ data or other CoP parameters. The current study demonstrated similar $CoP_{VEL\ AP}$ in people with and without CLBP, whereas previous research has demonstrated reduced[4,30] (n=24 and 22 per group respectively) and increased[2,31,32] (n=12, 12, and 10 per group respectively) CoP velocities. These mixed results suggest it likely that research demonstrating no difference between-groups has been conducted, however, due to publication bias may not have gained acceptance for publication. Interestingly, the studies conducted with the greater sample size, demonstrate poorer postural control in the asymptomatic groups, not the CLBP groups. Furthermore, findings from previous research[30,33] highlight that the small differences observed between groups in this study may be due to random error associated with the reliability of the measurement technique and not clinical change.

Differences in participant demographics (e.g. age[2,30], gender[32], or disability[4]), and methodological design (e.g. trial duration and repetitions[4,29,31]) make it difficult to directly compare study findings. Due to the numerous factors which may contribute to the variation in CoP outcomes reported, comparison of one study data with another is likely to reveal potential differences, however, choice of outcome measures and the number and duration of trials conducted in the current investigation improves the likelihood that data collected is reliable.

Gait

No differences were detected in spatio-temporal parameters between groups. In support of the current study findings, Al-Obaidi et al.[5] and Simmonds et al.[34] demonstrated no difference in cadence and self-selected walking speed respectively between people with and without CLBP (with a similar age and gender to those in the current study). However, research investigating participants with similar self-reported pain (mild to moderate) to the current study demonstrated reduced walking speed[5-8], stride time,[9-10] and stride length[5-6] in people with LBP. The current study averaged data from three trials for each participant, aiming to improve reliability[12] whereas other studies analysed data from only one walking trial,[5,8-9] possibly reducing data reliability. In addition, where other studies investigated predominantly[6] or all male participants,[8-9] the current study assessed male and female participants, enabling findings to be more representative of a general population. Furthermore, the current study assessed participants walking on normal ground, as opposed to on a treadmill,[7,9-10] hence, the current study findings are likely to be more representative of a natural walking pattern. These factors increase confidence that the current results are a more reliable and valid representation of gait in CLBP than that reported in previous research.[5-10]

In contrast to the current study, previous research has reported reduced hip range of movement in people with LBP during gait compared to asymptomatic individuals.[9] This may be due to co-contraction of muscles crossing the hip and pelvic region[35] limiting hip movement, or from participants reducing step length, and hence hip range, in an attempt to reduce potentially detrimental ground reaction forces at heel strike.[15,36] Reduced hip range demonstrated by Vogt et al.[9] occurred during treadmill gait, hence may not be representative of natural gait.[37] Furthermore, Vogt et al.[9] assessed hip range by attaching an electrical goniometer to the greater trochanter. This method of assessment provides less reliable data than the retro-reflective marker system utilised in the current study;[38,39] again increasing confidence that the current results are

likely a more valid representation of gait in people with CLBP. In the current study, due to the lack of difference in stride length between CLBP and asymptomatic individuals, the similar range of hip movement between the two groups was an expected finding.

Strengths and Limitations

The authors did not conduct a formal sample size calculation using minimal clinically important difference (MCID) data due to the absence of reported MCID data within the literature. However, standard error of measurements from repeatability studies for similar sample populations are reported in the literature for the more reliable postural stability outcome measure of COP_{VELAP}.[40] If minimal detectable change (MDC) is substituted for MCID in a sample size calculation (where alpha=0.05, Beta = 0.8, MDC for COP_{VELAP} = 5.4mm , standard deviations of groups = 1.09 and 1.52 where groups contain equal number of participants) this suggests that 6 participant would need to be recruited.

The authors note the convenience sample recruited in this study for the asymptomatic participants may not be representative of the general population; however potential asymptomatic participants were required to meet inclusion and exclusion criteria with a view to reducing this potential source of sampling bias. Sampling bias may have been reduced in the symptomatic sample as recruitment of participants occurred more broadly from a population with CLBP in multiple recruitment sites.

Although participants were matched for age and gender, the authors note that unaccounted confounders, such as anthropometric factors, level of physical activity, or kinesiophobia may have influenced study results. Given the small sample size in the current study, multivariate modelling was deemed inappropriate. Research investigating the influence of anthropometric factors (including body height, limb and trunk length, and body mass) on postural balance concluded postural balance assessed with eyes open and closed is only slightly[41] and moderately[42] influenced by these anthropometric variables; the variables that most influenced postural balance

being height and body mass index. The similarity of height and weight between groups in the current study (Table 1) is therefore reassuring.

The current study recruited CLBP participants from clinical populations,[20] who had sought medical opinion regarding their symptoms, hence, represented a typical population treated within physiotherapy departments. Previous research has recruited participants from alternative sources such as university populations[4] which may not be representative of the sub-group of CLBP individuals who seek medical guidance; hence caution should be taken if relating findings from such studies to a person with CLBP who is attending for treatment.

Further research

The velocity of the CoP is reported as the most reliable CoP parameter, however it is unclear if this measure is the most appropriate to detect difference in postural stability. Hence, a difference in postural control between the symptomatic and asymptomatic groups may have been present, but not detected. Alternative balance measures could be investigated, such as the forward reach test to determine whether more functional or challenging outcomes possess the necessary discriminatory value to detect differences in balance in people with and without CLBP and assist in confirming whether such differences exist.

Clinical implications

Based on the findings of this study, clinicians can be informed that standing postural stability, kinetic, kinematic and spatio-temporal parameters of gait in people with and without mild to moderate CLBP may not differ, and that treatments directed at influencing postural stability (for example, standing on a wobble board) or specific parameters of gait may be an unnecessary addition to a treatment programme.

CONCLUSIONS

In contrast to previous research, this study suggests that people with mild to moderate CLBP may present with similar standing postural control, hip moments and range of movement, and spatio-temporal parameters of gait to asymptomatic individuals.

What are the new findings?

- People with mild to moderate CLBP presented with similar standing postural control to asymptomatic individuals.
- During gait, spatio-temporal parameters were similar in people with and without CLBP.
- During gait, hip kinetics and kinematics were similar in people with and without CLBP.
- Treatments directed at influencing postural stability or specific parameters of gait may be an unnecessary addition to a treatment programme for people with CLBP.

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Contributors

CSM was the primary investigator, involved in all aspects of the study, including methodology, data collection, analysis and interpretation of data, and was the primary author of the article. All authors contributed to methodology, data interpretation, and editing of the manuscript for publication. All authors approved the final revision of the submitted manuscript. In addition, JSL received grant funding for the study, AS contributed to data collection.

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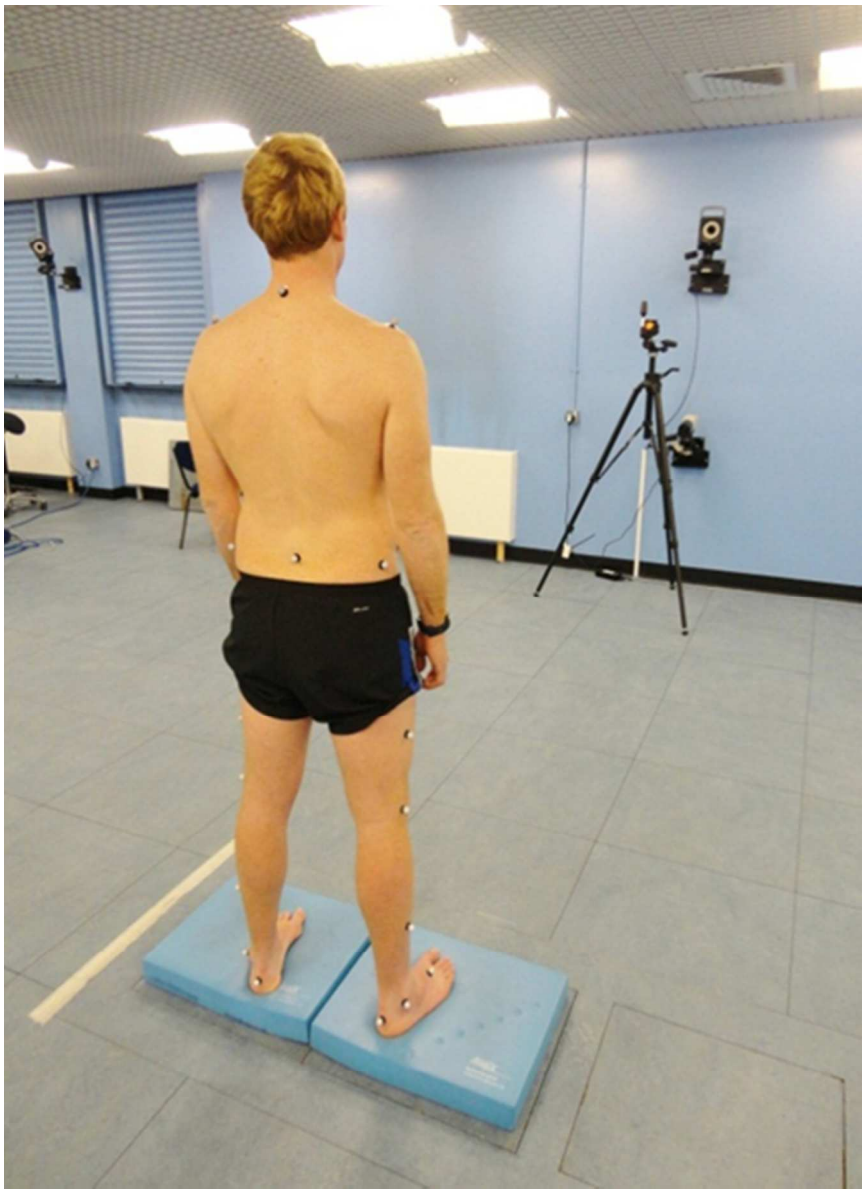
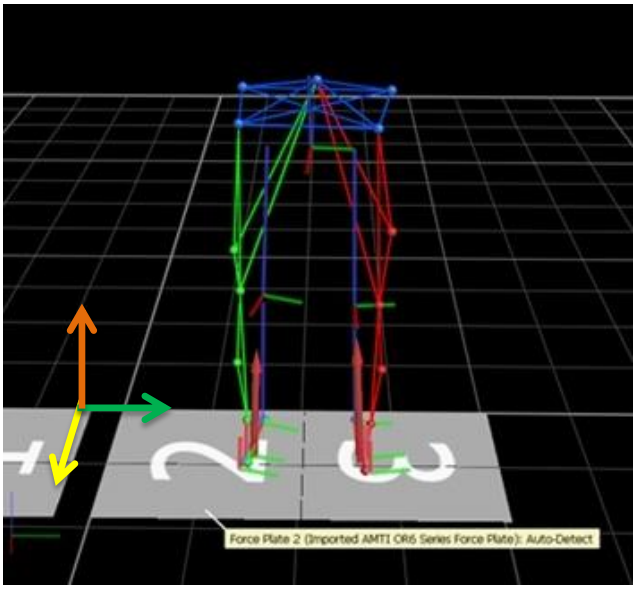


Figure 1. Participant with infra-red reflective markers in situ standing on foam cushions over-lying force plates.

Appendix 1

Centre of pressure calculations

Centre of pressure (CoP) calculations were made from the output from two force plates inset in the laboratory floor. The figure below demonstrates the x, y and z axes of the force plates. Yellow arrow represents the x-axis; green arrow, the y-axis; and orange arrow, the z-axis.



The x-coordinate of the CoP was calculated under each limb from the moments and forces produced by each plate with respect to the origin of the laboratory space, as follows:

$$x_{CoPl\_i} = \frac{-M_{yl\_i}}{F_{zl\_i}} + plate\ origin_{xl}$$

$$x_{CoPr\_i} = \frac{-M_{yr\_i}}{F_{zr\_i}} + plate\ origin_{xr}$$

where x_{CoPl_i}, x_{CoPr_i} are x- coordinates of the CoP under the left and right feet at time point i, and M_{yl_i}, M_{yr_i}, F_{zl_i}, F_{zr_i} are directional components of the moments and forces acting on the body from each force plate. These coordinates are expressed relative to the global coordinates of the laboratory space by a translation between the origin of the force plate and the origin of the laboratory (*plate origin*$_{xl}$, *plate origin*$_{xr}$) .

The x-coordinate of the CoP of the whole body was calculated by multiplying the x-coordinate of the CoP for each limb by the fraction of the total vertical force (F_z) acting through that limb, and adding the two terms together, as follows:

$$x_{CoP\_i} = x_{CoPl\_i} * \left(\frac{F_{zl\_i}}{F_{zl\_i} + F_{zr\_i}}\right) + x_{CoPr\_i} * \left(\frac{F_{zr\_i}}{F_{zl\_i} + F_{zr\_i}}\right)$$

where x_{CoP_i} is the x-coordinate of the CoP of the whole body.

Calculation of the root mean squared error of the centre of pressure in the antero-posterior direction ($CoP_{RMSE\ AP}$)

The root mean squared error of the CoP in the antero-posterior direction (x-direction) is given by:

$$CoP_{RMSE\_AP} = \sqrt{\sum_{i}^{N} \frac{\left(x_{CoP\_i} - \overline{x_{CoP\_i}}\right)^2}{N}}$$

where $\overline{x_{CoP\_i}}$ is the mean position of the x-coordinate of the CoP, and N is the number of time points in the trial.

Calculation of centre of pressure velocity in the antero-posterior direction ($CoP_{VEL\ AP}$)

The mean velocity of the CoP in the antero-posterior direction (x-direction) is given by:

$$CoP_{VEL\_AP} = \sum_{i} \frac{\left|x_{CoP\_i} - x_{CoP\_i-1}\right|}{N} * f_s$$

where f_s is the data sampling frequency.