TITLE: Lumbar Kinematic Pattern Variability during Gait and the Effects of Isolated Lumbar Extension Exercise in Chronic Low Back Pain

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Abstract

Chronic low back pain (CLBP) is a multifactorial condition with a variety of symptoms; one being gait variability. The lumbar spine and its musculature are important in controlling gait and in CLBP the lumbar extensors are often deconditioned. Because of this specific exercise for the lumbar extensors is often recommended. It was therefore of interest to examine relationships between lumbar kinematic variability during gait, with pain, disability and isolated lumbar extension (ILEX) strength in CLBP participants in addition to the effects of a 12 week intervention of ILEX exercise upon these variables. Twenty four CLBP participants were assessed for lumbar kinematics during gait, ILEX strength, pain (VAS), and disability (ODI) pre and post a 12 week intervention. Kinematic variability has been previously examined using Winter's coefficient of variation (CV). We utilised novel methods of differentiating waveform pattern (CV_p) and offset (CV_o) variability for comparison. Participants were randomised to either a training group undergoing 12 weeks of ILEX exercise 1x/week or a non-training control. Examination of Winters CV, CV_p and CV_o showed they incorporate largely different sources of variability and that CV_p best represents motor repeatability. Baseline comparisons also showed kinematic variables differed across movement planes; displacement and Winter's CV highest and similar in frontal and transverse planes, and CV_p and CV_o higher in the sagittal plane compared to frontal and transverse planes which were similar. Spearman's correlations of baseline data showed significant correlations between transverse plane CV_p and ILEX strength (r = -.411) and ODI (r = .401). However, VAS

was not correlated with CV_p in any plane. These findings contrast with earlier studies utilising Winter's CV. CV_p instead suggests that highest variability occurs in sagittal plane movement during gait in CLBP. After the ILEX intervention the training group showed a significant reduction in sagittal plane CV_p (-20.90±43.53%) indicating improved motor pattern replication. Considering the role of the lumbar extensors in gait, the relationship between both ILEX strength and ODI with transverse plane CV_p suggests gait variability may result in consequence of lumbar extensor deconditioning or disability accompanying CLBP. The ILEX intervention however appeared to specifically improve sagittal plane variability perhaps due to the plane of movement utilised during the exercise.

Key Words: Lumbar spine; Gait variability; VICON; MedX

1. Introduction

Chronic low back pain (CLBP) is a highly prevalent musculoskeletal disorder (Waddell & Burton. 2000; Walker et al. 2000) with costs amounting to billions worldwide (Katz, 2006; Freburger et al., 2009). Despite its prevalence, in as much as 85% of LBP cases no specific patho-anatomical diagnosis can be found (White & Gordon, 1982). However, more recently it is acknowledged as a multifactorial condition with a variety of associated dysfunctions (National Research Council, 1998; National Research Council & Institute of Medicine, 2001). One of the dysfunctions is atypical gait pattern (Waddell et al., 1997; Vogt et al., 2001).

Average movement amplitudes of the trunk and pelvis in CLBP participants are usually not significantly different from those seen in asymptomatic participants (Vogt et al., 2001; Lamoth et al., 2006[a]; Seay et al., 2011[a]). However despite this, CLBP participants do present differently in other aspects of lumbar spine movement, such as inability to adapt pelvis/trunk coordination phase differences during increases in

walking velocity,and greater stride-to-stride variability of lumbar spine kinematics with respect to the pelvis. Healthy participants demonstrate relatively low stride-to-stride variability in lumbar kinematic patterns during both level and incline gait (Vogt et al., 1999). However, greater stride-to-stride variability at the lumbar spine in all movement planes (Vogt et al., 2001), greater frontal plane coordination variability of the pelvis and trunk (Lamoth et al., 2006[a]; Seay et al 2011[b]) and more rigid transverse plane coordination variability of the pelvis and trunk (Lamoth et al., 2002; Lamoth et al., 2006[a]; van der Hoorn et al., 2012) is reported in CLBP participants compared with healthy controls. These atypical patterns are combined with poorer erector spinae activity adaptability to unexpected perturbations (Lamoth et al., 2004), or walking velocity changes (Lamoth et al., 2006[b]). In fact, the findings of numerous studies are suggestive of muscular dysfunction of the lumbar extensors during gait in those with CLBP compared with asymptomatic controls (Arendt-Nielsen et al., 1996; Vogt et al., 2003; Lamoth et al., 2004; Lamoth et al., 2006[a]; Lamoth et al., 2006[b]). Hanada et al. (2011) also report that where asymptomatic controls significantly activated their rectus abdominus and internal obliques more, symptomatic participants had significantly greater activation of the lumbar extensors. More recent work shows evidence of greater lumbar extensor activity in CLBP participants compared with controls (van der Hulst et al., 2010[a]), at a range walking velocities (van der Hulst et al., 2010[b]), and that neither disability nor fear of movement is associated with this greater activity (van der Hulst et al., 2010[a]).

The lumbar spine plays an important role in driving human bipedal gait (Gracovetsky, 1985). It is possible that the greater activation of the lumbar extensors, and altered lumbar spine kinematics during gait in CLBP participants, is a manifestation of the

lumbar extensor deconditioning (i.e. reduced strength/endurance, atrophy, and fatigability) commonly associated with CLBP (Steele et al., 2013[a]). Deconditioning therefore may impact upon motor control strategies and greater activation in the face of fatigue, due to deconditioning, could be a compensatory attempt to maintain control of the lumbar spine during gait. Hart et al., (2009) demonstrate that inducing fatigue in the lumbar extensors impacts lumbar kinematics during running gait of healthy participants and CLBP participants. Arjunan et al. (2009) also show significantly greater lumbar extensor activity during running gait in CLBP participants. Indeed, prospective evidence supports lumbar extensor deconditioning as being a risk factor for low back injury and pain (Biering-Sorenson, 1984; Luoto et al., 1995; Salminen et al., 1995; Lee et al., 1999; Sjolie et al., 2001). Thus it may be responsible for the development of the atypical gait associated with CLBP also.

Exercise programs have been successful in improving gait variability in older individuals and improvement appears to be in part determined by gains in strength (Hausdorff et al., 2001). Specific exercise for the lumbar extensors, however, is often used to specifically address the lumbar extensor deconditioning associated with CLBP (Mayer et al., 2008) and thus may be valuable in addressing the associated lumbar spine kinematic gait variability also. Varied types of exercise based interventions (Pilates, trunk extensions, stability exercise, transverse abdominus exercise) elicit improvements in gait control in CLBP participants (Carpes et al., 2008; Tsao & Hodges, 2008; Da Fonseca et al., 2009). However, a more specific means of training the lumbar extensors comes in the form of isolated lumbar extension (ILEX) exercise (Steele et al., 2013[b]). Its efficacy in strengthening the lumbar extensors as well as improving pain and disability in CLBP participants have

been demonstrated in numerous studies (Smith et al., 2011; Bruce-Low et al., 2012; Steele et al., 2013[c]). In addition, recent work has found that improvement in ILEX strength resulting from a strengthening program predicts improvement in gait endurance in CLBP participants (Vincent et al., 2013). This specific form of exercise however has yet to be examined for its effects upon lumbar kinematics during gait. Considering this it was therefore of interest in the present study to examine the relationships between lumbar kinematic variability during gait, with pain, disability and ILEX strength and also the effects of an ILEX exercise intervention upon lumbar kinematic variability during gait in participants with CLBP.

2. Methods

2.1 Study Design

A randomised controlled trial design was adopted with one experimental group and a control group. The study was part of a wider investigation examining ILEX in CLBP participants which has been published in part elsewhere (Steele et al., 2013[c]). The original study sought to examine the effect of range of motion (ROM) during exercise upon ILEX strength, ROM, pain and disability. Gait data were also collected as part of this study to be examined as an outcome measure though it was not hypothesised that the different ROM groups (FULLROM & LimROM) would differ in this outcome. Data analysis confirmed there to be no differences between the two intervention groups for gait variable outcomes. Thus in this present study the two experimental groups from the wider investigation (FullROM & LimROM) were combined to form a single experimental group who had performed training using ILEX in order to increase the sample size of the intervention group for statistical comparison. Here the kinematic data are described only. The study was approved by the NHS National

Research Ethics Service, Southampton & South West Hampshire Research Ethics Committee B (REC Reference: 11/H0504/9) and the Centre for Health, Exercise and Sport Science ethics committee at Southampton Solent University (SSU) and was conducted within the Sport Science Laboratories at SSU.

2.2 Participants

Thirty eight participants (males n = 21, females n = 17) were initially identified and recruited by posters, group email and word of mouth from Southampton Solent University and the surrounding locality. Direct referral was also provided from a local private chiropractor in addition to posters in their practice. A power analysis examining effect size for ILEX strength from ILEX intervention (ES = 1.48) was conducted to determine participant numbers and showed that each group required 7 to meet the required power of 0.8 at an alpha value of $p \leq .0.05$. This power analysis is described elsewhere (Steele et al., 2013[c]). No previous work has examined effect sizes of the kinematic variables considered here as outcome measures and so, though the study was considered to be adequately powered with respect to ILEX strength outcomes, there was the possibility that a type II error may result with respect to kinematic data. In an attempt to reduce this likelihood this number of participants was combined with 5 kinematic trials per participant which is considered sufficient for achieving adequate statistical power in a study of kinematic data utilising single subject statistical methods (Bates et al., 1992).

Inclusion criteria were as follows; participants suffered from non-specific low back pain having lasted longer than 12 weeks (Frymoyer, 1988) and had no medical condition for which resistance training would be contraindicated. Exclusion criteria

were as follows; participants must have no medical condition for which movement therapy would be contraindicated. These included: acute (not re-occurring) low back injury occurring within the last 12 weeks, pregnancy, evidence of sciatic nerve root compression (sciatica), leg pain radiating to below the knee, paraesthesia (tingling or numbness), current tension sign, lower limb motor deficit, current disc herniation, previous vertebral fractures or other major structural abnormalities. All participants were cleared prior to involvement in the study by either their General Practitioner or the Chiropractor in the research group and provided written informed consent.

Figure 1 shows a CONSORT diagram highlighting the participant numbers for enrolment, allocation, follow-up and analysis stages. After initial drop outs thirty one participants were randomised using an randomisation program (Research Randomizer vs. 3.0) to one of three participant groups; a full ROM training group (FullROM; n = 12), a limited ROM training group (training using the mid 50% of their ROM) (LimROM; n = 10), and a control group (n = 9) who did not train but continued with any treatment or intervention (or lack thereof) they were currently undertaking. As noted, the two experimental groups were combined for analysis in this particular part of the investigation.

2.3 Equipment

Participants' stature was measured using a stadiometer (Holtan ltd, Crymych, Dyfed), body mass measured using scales (SECA, Germany) and Body Mass Index (BMI) calculated. Isometric ILEX strength testing, ROM and training were performed using the MedX Lumbar Extension Machine (MedX, Ocala, Florida; figure 1). The lumbar extension machine has been shown to be reliable in assessing isometric

strength at repeated angles in asymptomatic (r = 0.81 to 0.97; Graves et al, 1990) and symptomatic participants (r = 0.57 to 0.93; Robinson et al. 1992[1]), and valid in measurement through removal of gravitational effects (Pollock et al. 1991) and pelvic movement (Inanami, 1991). Pain was measured using a 100mm point visual analogue scale (VAS; Ogon et al. 1996), and disability measured using the revised Oswestry disability index (ODI; Fairbank et al. 1980). Gait kinematic variables were captured at 500hz using a 10 MX T20 camera three dimensional motion capture system (Vicon, Oxford) and analysed using both Vicon Nexus software version 1.4.116 (Vicon, Oxford), MATLAB version R2012a (MathWorks, Cambridge) and Microsoft Excel version 2010 (Microsoft, Reading).

2.4 Participant Testing

Isometric ILEX strength was tested twice, on separate days (at least 72 hours apart in order to avoid the effects of residual fatigue or soreness) both before and after the intervention. Each test using the lumbar extension machine involved maximal voluntary isometric contractions at various angles through the participant's full ROM. Details of the full test protocol using the lumbar extension machine and details of the restraint mechanisms have been documented previously elsewhere (Graves et al. 1990). During the first and second to last visit to the laboratory, participants were required to complete the VAS and the ODI. Gait data was collected using the Vicon system during the third visit to the laboratory, and also during the participant's final visit to the laboratory after the intervention period.

2.5 Three dimensional motion analyses

Due to the lumbar spine's capacity to rotate about three orthogonal axes, a three dimensional approach was used for data collection. Ten cameras were set up and angled in a manner so as to reduce hidden spots that might obscure data collection. The cameras identified reflective markers attached to the participant and output three dimensional coordinates for each marker. Data were recorded for 5 walking trials both pre and post intervention. Participants walked barefoot from one end of a marked runway to the other that was 8 metres in length at their free walking speed. At least one full gait cycle was captured per trial.

2.4 Biomechanical Model

The body of interest for the current study was the lumbar spine considered from S1 to T12 relative to the pelvis. For the purpose of analysis the lumbar spine was modelled as a rigid segment. The reasoning for not considering intervertebral segment movements was due to the small segments ranging from S2 to T10 always bending laterally toward the support leg with little variation between segments (Syczewska et al., 1999). Lumbar spine data were collected through three axes using the same model previously described by Schache et al. (2002[a]), which has been shown to have high overall repeatability of angular parameters (Schache et al., 2002[b]).

2.5 Marker Set Up

Markers were placed by the same investigator for all gait trials. Markers were placed using double sided adhesive tape over anatomical landmarks on the pelvis at both anterior superior iliac spines (ASIS) and at the midpoint of the posterior superior iliac spine (PSIS). Reflective markers were also used upon a thoraco-lumbar marker

cluster similar to that used by Schache et al., (2002[1a]; 2002[b]). As with the biomechanical model, this marker set up has been previously described elsewhere (Schache et al., 2002[a]; Schache et al., 2002[b]). The only alteration in this present study was the use of a flexible based wand marker for the thoraco-lumbar cluster.

2.6 Kinematic Data

Variability of angular kinematics of the lumbar spine about the three described axes relative to the pelvic segment was of primary interest (i.e. movement of the thoraco-lumbar marker cluster with respect to the pelvic markers). Angular data were filtered using a low pass Butterworth filter (fourth order, optimal cutoff frequency determined for each individual participant as sum of residuals closest to zero examining 2Hz, 4Hz, 6Hz, 8Hz, 10Hz, and 12Hz) and normalised to percentage gait cycle corresponding to initial right heel contact (0%) and subsequent right heel contact (100%) for the first full gate cycle captured during each trial. Heel contacts were identified as the lowest vertical displacement of a right heel marker.

Intra-subject variability in the mean ensemble average has been typically calculated using Winter's (1983) CV in studies of lumbar kinematic variability in CLBP (Vogt et al., 2001). Thus to ensure comparability between the population used in this study with the CVs reported in earlier study of CLBP participants, intra-subject variability was calculated using Winter's CV. However, the use of this method has recently been criticised due to the effect of waveform mean offsets altering relative variability away from the true variability in the system (O'Dwyer et al., 2009). O'Dwyer et al. (2009) note that variability of mean offsets and waveform pattern variability should be calculated separately to account for the different information they provide; CV_o

being determined by the reference frame used, identification of anatomical landmarks, markers and their configuration, whereas CV_p is more representative of repeatability of motor performance. Adding to this, the model used in this study has been examined for within-day repeatability previously and it was reported that marker reapplication errors and their effect upon daily mean offsets were the main source of concern (Schache et al., 2002[2]). Thus both CV_p and CV_o were also calculated to allow differentiation of offset variability from pattern variability, the latter being better representative of motor performance repeatability (For details on calculation please refer to O'Dwyer et al., 2009).

2.7 Participant Training

Training was conducted at a frequency of 1x/week for a period of 12 weeks. This frequency of training has been shown to significantly improve ILEX strength and was chosen over more frequent training due to potential for overtraining when the lumbar extensor muscles are isolated (Graves et al. 1990[2]). Also a second weekly training session offers no further improvements in symptomatic participants (Bruce-Low et al., 2012). Twelve weeks was the chosen duration as Carpenter et al (1991) have demonstrated that strength improvement from ILEX training occurs largely within the first 12 weeks. Both groups performed one set of variable resistance ILEX exercise. The FullROM group used their full ROM while the LimROM group only used the mid 50% of their individual ROM (Steele et al., 2013[c]). Resistance load was 80% of max recorded tested functional torque (TFT) during maximal isometric testing for both groups and repetitions performed until momentary muscular failure in order to control for intensity of effort (Steele, 2013). Repetitions were performed taking at least 2 seconds to complete the concentric phase, holding for 1 second in full extension and

taking at least 4 seconds for the eccentric phase. Resistance load was increased by 5% in the next session once the participant was able to continue exercise for over 105 seconds using their current load before achieving failure.

2.8 Data Analysis

Eligibility for analysis required participants to have completed 75% of the intervention within the 12 week period. Twenty four participants' data (Males, n = 13; Females, n = 11) were available for analysis after allowing for attrition. Thus the number of participants combined with 5 trials per participant was sufficient for achieving adequate statistical power. Isometric ILEX strength, recorded in units of torque, was measured across the participants' full ROM as foot pounds ($ft.llbs^{-1}$) and converted to Newton metres (Nm) using a correction of 1.356. Because of individual differences between participants for lumbar ROM, ILEX strength data was averaged across all angles tested. Mean values for angular displacements, stride-to-stride intra-subject variability using Winter's CV, CV_p and CV_o, were calculated for lumbar spine kinematics relative to the pelvis across all three planes of movement.

Demographic data met assumptions of normality and homogeneity of variance and thus were compared between groups at baseline using an independent samples t-test. Kinematic data did not meet assumptions of normality or homogeneity of variance as is typical for this type of data (Bates et al., 2004). Thus non-parametric statistical analysis was used and baseline kinematic data was compared between groups using the Mann Whitney-U exact test to check that randomisation had succeeded for these variables. Previous researchers have performed gender comparisons (Crosbie et al., 1997; Vogt et al., 2001) and so in this study using

unique methods of analysis male and female differences in baseline demographic characteristics were examined using an independent samples t-test, while kinematics, VAS, ODI, and ILEX strength, were examined using a Mann Whitney-U exact test. For baseline kinematic variables (including means for displacements, stride-to-stride intra-subject variability using Winter's CV, CV_p and CV_o), spearman's correlations were examined between them and VAS, ODI, and ILEX strength.

In examining the effects of the ILEX intervention the independent variable examined was participant group (i.e. Combined ILEX training or Control) and dependent variables were the absolute change from pre to post for kinematic variables examined, VAS, ODI and ILEX strength. Wilcoxon Signed Ranks Exact test was used to compare across the independent conditions. Statistical analysis was performed using SPSS statistics computer package (vs.20) and $p \leq .05$ set as the limit for statistical significance.

3. Results

3.1 Participant Demographics

Participant demographics, pain, disability and ILEX strength data are shown in Table 1 for groups. Comparison between groups revealed that the majority of demographic variables at baseline did not significantly differ thus it was considered that randomisation had been successful. The only significantly different characteristic between groups was VAS score ($t_{(22)} = 2.420$, $p = 0.024$).

Gender comparisons also revealed males had significantly greater stature ($t_{(21)} = 6.087$, $p < 0.0001$), body mass ($t_{(21)} = 4.700$, $p < 0.0001$), BMI ($t_{(21)} = 2.674$, $p =$

0.014) and ILEX strength ($t_{(22)}$ = 5.879, p < 0.0001) than females. No significant differences between males and females were found for age, symptom duration, VAS or ODI.

3.2 Baseline Kinematic Data

Between group comparisons again revealed that the majority of kinematic variables did not significantly differ at baseline. Only sagittal CV_o (U = 23.000, Z = -2.318, p = 0.019), and both transverse Winters CV and CV_o (respectively; U = 17.000, Z = -2.699, p = 0.005) differed between groups.

No significant differences between males and females were observed for the majority of kinematic variables. However, respectively for men compared with women, men exhibited lower frontal displacement (U = 12.000, Z = -3.447, p < 0.0001), greater frontal CV_p (U = 30.000, Z = -2.404, p = 0.008) and lower sagittal displacement (U = 31.000, Z = -2.347, p = 0.009).

Due to the use of a new method of determining ensemble average variation in this study (CV_p and CV_o ;O'Dwyer et al., 2009), compared with others use of Winters CV research (Vogt et al., 2001), baseline data was pooled for all participants in order to compare Winters CV, CV_p, and CV_o in this population of CLBP participants. Displacement and Winter's CV were highest and similar in frontal and transverse planes. Contrastingly CV_p and CV_o were higher in the sagittal plane than in frontal and transverse planes which were both also similar. Figure 2 presents a comparison

of these pooled data showing mean and SDs with Winter's CV, and mean and SDs transformed to zero with both CV_p and CV_o.

Spearman's correlations revealed a significant moderate positive correlation between VAS and only sagittal plane Winters CV (r = .411, p = 0.023). Significant moderate positive correlations were found between ODI and sagittal plane Winters CV (r = .457, p = 0.012), transverse plane Winters CV (r = .404, p = 0.025) and transverse plane CV_p (r = .401, p 0.026). Significant moderate negative correlations were also found between ILEX strength and frontal plane CV_o(r = -.370, p = 0.045), sagittal plane Winters CV (r = -.467, p =0.014), transverse plane Winters CV (r = -.435, p = 0.021), transverse plane CV_p (r = -.411, p = 0.029), transverse plane CV_o (r = -.378, p = 0.042) and a significant moderate positive correlation with transverse plane displacement (r = .442, p =0.020).

3.3 Effects of Intervention upon Kinematic Variables

Table 2 shows pre and post data for displacement, Winters CV, CV_p and CV_o. Wilcoxon Signed Ranks Exact test revealed significant changes from pre to post only for sagittal plane CV_p ($W_{(16)}$, Z = -1.728, p = 0.044) in the training group only suggesting improvement in stride to stride waveform pattern replication after the intervention.

4. Discussion

This study of lumbar kinematic variability during gait in CLBP participants yields several interesting and unique results: 1) sagittal plane lumbar kinematic waveform patterns appear to be considerably more variable in CLBP than frontal or transverse

planes, this being observed through the use of unique methods of differentiating offset variability from pattern variability in this population and in contrast to earlier studies using Winters CV, 2) transverse plane lumbar spine pattern variability is significantly correlated with ILEX strength and ODI, and 3) the use of a 12 week ILEX resistance training intervention produces significant improvement in sagittal plane variability during gait in CLBP participants. These findings potentially offer further understanding of the nature of the relationships between CLBP, gait variability and lumbar extensor deconditioning.

Within this study however the foremost interest was the repeatability of lumbar spine movement patterns exhibited (intra-subject stride-to-stride variability) as, despite similar average movements occurring at the lumbar spine, symptomatic participants appear less able to replicate these consistently (Vogt et al., 2001). Vogt et al. (2001) reported data using Winter's CV suggesting lumbar movement variability during gait was significantly higher in CLBP participants compared with asymptomatic controls, and that both sagittal and transverse plane variability was greater than frontal plane variability. In order to compare our results with this previous research we calculated Winter's CV for the present study's data. Our results for Winter's CV differed from those of Vogt et al. (2001) in that sagittal plane variability appears lowest in our data (Vogt et al. 2001 – 26.93%; Present study – 6.73%), and that both frontal and transverse plane variability was slightly higher (Vogt et al., 2001 – 14.87% and 26.45% frontal/transverse respectively; Present study – 34.74% and 38.66% frontal/transverse respectively). The considerable difference in sagittal plane Winter's CV might be accounted for by the large mean offset in the waveform of our data. Vogt et al. (2001) calibrated their measurements to angles during the standing

posture in order to zero the measurements whereas in the present study they were not. Our sagittal plane data were instead closer in similarity to those of Lamoth et al. (2002[a]). Thus a large mean offset value effectively deflates the value calculated for Winter's CV (O'Dwyer et al., 2009). Because of this O'Dwyer et al. (2009) have suggested the use of methods to differentiate the offset from calculation of the variability in the waveform pattern; the latter they suggest being far more representative of movement replication whereas the offset incorporates a greater degree of other variance sources (i.e. marker error). Indeed Schache et al. (2002[b]) have shown that although high within-day repeatability was displayed for the model adopted in the present study, angular parameters were most susceptible to marker reapplication errors from repeated measures and affected waveform offset.

Our data show that CV_p differs considerably from variation calculated using Winter's CV. Sagittal plane variation (106.44%) is more than double the variation seen in the frontal (45.07%) and transverse planes (42.81%). Figure 2 shows that the CV_p better represents the absolute variation in the waveform (the standard deviations depicted by the dotted lines) as noted by the sagittal plane standard deviation bandwidth being twice as wide as the frontal and transverse planes. Winter's CV on the other hand does not represent this in the raw data as it is clear that both frontal and transverse plane variance are not ~5 times larger than sagittal plane variance. This further demonstrates, as O'Dwyer et al. (2009) suggest, that differentiation of offset and pattern variability is better representative of motor performance repeatability and less affected by inter-individual marker application errors affecting mean offset values for individual participants.

CV_p has not been calculated in CLBP participants previously and thus it is not possible to verify whether this greater sagittal plane pattern variability is a typical characteristic of their gait. Nor is it possible to define the clinical meaning of this in comparison to healthy gait as CV_p has also not been reported on lumbar spine gait kinematics in asymptomatic participants to the author's knowledge. Our results from correlation analysis suggest that those with lower ILEX strength exhibit higher sagittal and transverse plane variability when considering Winter's CV. However, the inherent limitation of this method must be taken into account. Yet, despite the high sagittal plane CV_p in comparison to other planes of movement, our baseline correlation results suggest that there is instead a relationship between ILEX strength and transverse plane kinematics; lower transverse displacement and higher CV_p being associated with lower ILEX strength. It might be speculated upon that this relationship in CLBP participants may be a consequence of the lumbar extensor deconditioning frequently associated with this population (Steele et al., 2013[a]). Indeed it could be recalled that extensor fatigue impacts upon lumbar kinematics during gait emphasising the link between deconditioning and gait abnormality (Harts et al., 2009).

It seems reasonable that in a pathology such as CLBP, wherein there is an associated deconditioning of what appears to be a critically important musculature for controlling gait (Gracovetsky, 1985; Thorstensson et al. 1982; Callaghan et al. 1999; Winter et al. 1993), that the deconditioning of this musculature might be considered as potentially responsible for altered motor control. Indeed our results tend towards supporting this with respect to transverse plane CV_p during gait,

however, that the correlations reported were only modest highlights that they are not the only influencing factor. It might be noted that some authors have reported that transverse plane kinematics typically show *lower* variability in those with CLBP (Lamoth et al., 2002; Lamoth et al., 2006[a]; van der Hoorn et al., 2012). However, these studies have examined the *coordination* of the trunk and pelvis and variability in the phase differences whereas the present study has instead examined the lumbar spines waveform relative to the pelvis. This difference in methodology may account for the difference in conclusions between these studies. Our baseline results did also suggest that low ILEX was associated with smaller transverse displacements. Perhaps transverse movement is more rigid in CLBP, yet within that smaller range of movement there is poor waveform pattern repeatability. The rigidity seen in transverse kinematic coordination in CLBP (Lamoth et al., 2002; Lamoth et al., 2006[a]; van der Hoorn et al., 2012) may yet still be a manifestation of lumbar extensor deconditioning. Considering this it may be of future interest to examine the relationship between ILEX and trunk/pelvis coordination in those with CLBP.

In addition, our results provide further evidence against the idea that pain *per se* may cause the variability seen during gait in CLBP. Although a significant positive correlation was found between VAS and Winters CV there was no significant correlation found between VAS and CV_p or any other kinematic variable supporting the findings of others that pain presence appears to not be associated with gait variability (Lamoth et al., 2004; Anders et al., 2005; Seay et al., 2011[a]). There was however also a significant correlation between ODI and transverse plane CV_p. Considering the multifactorial nature of CLBP it would be reasonable then to consider this evidence suggests that gait variability is potentially a symptom

associated with CLBP that may result as a consequence of deconditioning of the lumbar extensors or the disability accompanying CLBP. However, it is also possible that the absence of direct correlation instead suggests that the consequences of pain may be responsible. Though neither disability nor fear of movement is associated with greater lumbar extensor activity during gait in CLBP (van der Hulst et al., 2010[a]), different cognitive strategies may be associated with either greater activity (catastrophizing), or greater relaxation during double support (distraction), suggesting some influence of pain consequences upon the lumbar extensors during gait (van der Hulst et al., 2010[c]).

With regards to the baseline observations a limitation within the present study was the lack of a comparable healthy control group due to the study's initial design as an experimental trial. Our data on Winter's CV suggests that our CLBP participants show higher lumbar spine variability compared to data from normal participants in earlier studies (Vogt et al., 1999; Vogt et al., 2001). Thus it might seem reasonable to speculate that variability identified from CV_p data would likely be greater in the CLBP participants in this study compared with healthy controls. However, CV_p has not been calculated for lumbar spine kinematics in healthy participants as of yet to the author's knowledge. Thus future work in healthy participants should utilise this method (O'Dwyer et al., 2009) in order to produce normative data in order to conduct comparisons and also provide data in order to judge improvement from clinical intervention.

The baseline analysis showing weak ILEX strength to be associated with greater variability however lends support to the notion that exercise might be an intervention

worthy of examination. Indeed previous studies have provided support for exercise based interventions on improving aspects of gait variability including muscle activation (Tsao & Hodges, 2008), ground reaction force parameters (Da Fonseca et al., 2009) and displacements during gait (Carpes et al., 2008). However, none have examined lumbar kinematic variability during gait, nor has prior work utilised specific exercise designed to isolate the lumbar extensors. Within the present study an intervention employing a highly specific form of exercise evidenced as most effective for conditioning the lumbar extensors was used (Steele et al., 2013[b]). The results indicate that ILEX resistance training produced a significant reduction in sagittal plane CV_p suggesting greater ability for participants to replicate motor patterns in this plane during gait.

Baseline data indicated a relationship between transverse CV_p and ILEX strength yet the intervention aimed at improving ILEX strength resulted in reduced sagittal CV_p. Unlike previous research examining Winters CV finding that it was low in CLBP participants (Vogt et al., 2001), sagittal plane CV_p was found to be highest in this population of CLBP and so may play a role in the improvements observed being that there was the greatest scope for improvement. However, the significant improvement (-20.90$\pm$43.53%) in sagittal CV_p may suggest a specific intervention effect due to the plane of motion that ILEX exercise is performed through. An exercise device similar to the one used in this study for ILEX also exists that allows pelvic restraint for torso rotation through the transverse plane to be performed in isolation (Torso Rotation Machine, MedX, Ocala, Florida). Mooney et al. (2001), after demonstrating that the latissumus dorsi and contralateral gluteus maximus follow a reciprocal relationship in activity during gait presumably contributing to control about the transverse plane,

further examined the effects of torso rotation exercise. In this study Mooney et al. (2001) examined activation during torso rotation exercise showing that abnormal activation patterns were present in symptomatic participants compared with controls. After a training intervention of progressive resistance training using the torso rotation device this activation had returned to normal levels of activity seen in asymptomatic participants. However, despite reporting EMG results for the latissumus and gluteus to clarify their role during gait, Mooney et al. (2001) did not perform pre and post intervention measurements to identify if any change had occurred in muscular control during gait in the symptomatic participants. In light of the results of the present study it is suggested that future research perhaps quantify whether plane of movement specific training may produce consequent plane of movement specific changes in control of the lumbar spine during gait. For example, whether torso rotation may perhaps improve transverse CV_p.

5. Conclusions

The results of this study have provided novel information on lumbar spine kinematic variability during gait in CLBP through the use of recently suggested methods of analysing pattern variability. These new findings are in contrast to earlier ones utilising Winter's CV and instead suggest that the highest variability is observed in sagittal plane lumbar movement during gait in CLBP. Further to this, there was a significant relationship between both ILEX strength and ODI with transverse plane lumbar CV_p. And, a lack of relationship between VAS and CV_p in any plane measured during gait. An intervention utilising 12 weeks of ILEX resistance exercise was found to significantly improve sagittal plane CV_p indicating improved motor pattern replication. These findings are important as they demonstrate that improvements

may be possible in various factors typically associated with CLBP through use of ILEX exercise.

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