Fear of movement is not associated with trunk movement variability during gait in patients with low back pain

Veeger, Thom T.J.; van Trigt, Bart; Hu, Hai; Bruijn, Sjoerd M.; van Dieën, Jaap H.

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Basic Science

Fear of movement is not associated with trunk movement variability during gait in patients with low back pain

Thom T.J. Veeger, MSc[a], Bart van Trigt, MSc[b], Hai Hu, PhD, MD[c],
Sjoerd M. Bruijn, PhD[d], Jaap H. van Dieën, PhD[d],[*]

[a] *C.J. Gorter Center for High Field MRI, Department of Radiology, Leiden University Medical Center, Leiden, the Netherlands*
[b] *Department of Biomechanical Engineering, Delft University of Technology, Delft, the Netherlands*
[c] *Orthopedic Biomechanical Laboratory of the Department of Othopedic Surgery, Shanghai Jiaotong University Affliated Sixth People's Hospital, Shanghai, P.R. China.*
[d] *MOVE Research Institute Amsterdam, VU University Amsterdam, Amsterdam, the Netherlands*

Abstract

BACKGROUND: Literature describing differences in motor control between low back pain (LBP) patients and healthy controls is very inconsistent, which may be an indication for the existence of subgroups. Pain-related psychological factors might play a role causing these differences.

PURPOSE: To examine the relation between fear of movement and variability of kinematics and muscle activation during gait in LBP patients.

STUDY DESIGN: Cross-sectional experimental design.

PATIENT SAMPLE: Thirty-one Chinese LBP patients.

OUTCOME MEASURES: Self-report measures: Visual Analog Score for pain; TAMPA-score; Physiologic measures: electromyography, range of motion.

FUNCTIONAL MEASURES: LBP history; the physical load of profession, physical activity.

METHODS: Patients were divided in high and low fear of movement groups. Participants walked on a treadmill at four speeds: very slow, slow, preferred and fast. Kinematics of the thorax and the pelvis were recorded, together with the electromyography of five bilateral trunk muscle pairs. Kinematic and electromyography data were analysed in terms of stride-to-stride pattern variability. Factor analysis was applied to assess interdependence of 11 variability measures. To test for differences between groups, a mixed-design multivariate analysis of variance was conducted.

RESULTS: Kinematic variability and variability of muscle activation consistently loaded on different factors and thus represented different underlying variables. No significant Group effects on variability of kinematics and muscle activation were found (Hotelling's Trace F=0.237; 0.396, p=.959; .846, respectively). Speed significantly decreased kinematic variability and increased variability in muscle activation (Hotelling's Trace F=8.363; 4.595, p<.0001; <.0001, respectively). No significant interactions between Group and Speed were found (Hotelling's Trace F=0.204; 0.100, p=.762; .963, respectively).

CONCLUSIONS: The results of this study do not support the hypothesis that variability in trunk kinematics and trunk muscle activation during gait in LBP patients are associated with fear of movement. © 2020 The Author(s). Published by Elsevier Inc. This is an open access article under the CC BY license. (http://creativecommons.org/licenses/by/4.0/)

Keywords: Electromyography; Gait; Kinematics

*Corresponding author. MOVE Research Institute Amsterdam, VU University Amsterdam, Amsterdam, the Netherlands.
E-mail address:* j.van.dieen@vu.nl (J.H. van Dieën).

Introduction

Low back pain (LBP) is the number one disabling pathology world-wide [1]; about 80% of all adults will suffer from LBP at some point in their life, of which 20% will develop chronic LBP, defined as pain that persists for 12 weeks or longer [2]. A recent study indicated that motor control issues are predictive of disability in chronic LBP patients [3] and systematic reviews [4−6] have concluded that motor control exercise is moderately effective in treating these patients. However, these reviews also suggest that further research should determine which subgroups of LBP patients respond best to motor control exercise [4−6]. If the presentation of motor control issues is variable between patients, some patients may require motor control exercise, and others not. So, do clinically relevant differences in motor control exist between LBP patients, and if so, what are these, and what causes these differences? Much research has been done to describe differences in motor control between LBP patients and healthy controls. Generally speaking, results were quite inconsistent, with some studies reporting differences between patients and controls, and other studies reporting no differences, or even opposite findings [7−11]. As an example, both increased and decreased variability of trunk movement of gait in LBP patients compared to healthy controls have been reported [12−16]. Van Dieën et al. [7] proposed that the inconsistency in findings on variability might reflect the existence of two subgroups: a group with 'tight' control, who were suggested to respond to pain with an attempt to tighten control over trunk movement, and a 'loose' control group, in whom pain interferes with the precision of motor control.

The question arises what determines whether a patient is in one group or in the other. Psychological factors related to pain, such as fear of movement, may promote tight control over trunk movement [17]. In support of this notion, fear of movement and fear-avoidance beliefs were found to be positively associated with trunk stiffness in LBP patients during a semi-seated perturbation task [18]. Also, levels of trunk muscle activation were increased while variability of trunk muscle activation was decreased in patients with high fear of pain, fear-avoidance beliefs and pain catastrophizing [19−22]. Trunk movement variability has been compared between patients with LBP and controls in several studies, specifically during walking, again with inconsistent results [13,15,16,23]. However, the association between movement variability and pain-related psychological factors has, to our knowledge, not been studied.

The aim of the present study, therefore, was to compare variability of trunk kinematics and of trunk muscle activation over strides during walking between LBP patients with high and low fear of movement. We hypothesized that patients with more fear of movement show a lower variability of trunk kinematics and trunk muscle activation, compared to patients with less fear of movement.

Methods

Subjects

Participants with LBP, recruited at the Shanghai Jiaotong University, Affiliated Sixth People's Hospital in China, who volunteered for this study were first asked to fill in were first asked to fill in The Tampa scale for Kinesiophobia (TAMPA), to assess their fear of movement. We used a validated Chinese version of the TAMPA questionnaire which had been validated in patients with LBP [24] Besides, information about their LBP history, the physical load of their jobs, their physical activity, their weight and height, and their current pain level on the Visual Analog Scale (VAS) were registered. Only patients with non-specific chronic LBP were selected. Patients with a trauma, neurologic symptoms, tumours, infections or patients suffering from a neurologic and/or musculoskeletal disorder unrelated to LBP were excluded from this study. Patients with a body mass index higher than 27 were also excluded from this study, since this would have a negative effect on the quality of EMG data.

To determine an appropriate sample size, an a priori power analysis was performed in the software program G*Power [25]. Because little information was available, we estimated the effect size based on published differences between LBP and healthy controls. We hypothesized that the LBP group actually consists of subgroups showing opposite effects, as we explained in the introduction. Therefore, we hypothesized that the differences between subgroups based on fear of movement would be more pronounced than between LBP and controls. Based on this hypothesis, we assumed a large effect size of 0.4. We performed the a priori power analysis for a repeated measures MANOVA with between factors and used a power of 0.8 and assumed a correlation between repeated measures of 0.5. This resulted in a needed sample size of 34 in total.

After the selection, 31 patients were asked to participate in the study, 10 men and 21 women with an average and median age of 33 and a median TAMPA-score of 43 (Table 1). Before starting the experiment, the patients signed an informed consent. The study was approved by the Ethical Committee of Shanghai Sixth People's Hospital, Republic of China (2016-45).

Procedures

Before the experiments started, participants walked on a treadmill to familiarize themselves with treadmill walking and to determine their preferred walking speed. To find the preferred walking speed, the participants began to walk on the treadmill at a slow speed of 0.3 m/s and the speed was gradually increased by 0.1 m/s about every 15 seconds. After each increase the participant was asked whether the new speed was more comfortable than the previous. When the participant indicated that the new speed was more comfortable, the speed was increased again, until the new speed

Table 1
Descriptive statistics of participant demographics and clinical characteristics with mean and standard deviation (SD) for normally distributed variables and median and interquartile range (IQR) for non-normally distributed variables (*)

Variable (unit)	Minimum	Maximum	Mean/Median*	SD/IQR*
Gender	Male: 10 Female:21			
Age (years)	24	53	33*	10*
Length (cm)	145.0	196.0	164.06	10.79
Weight (kg)	39.3	85	59.49	12.14
BMI	17.4	27.0	21.93	2.63
TAMPA	32	56	42.7	6.0
Months of pain (mo)	3	120	36*	58.5*
Visual Analog Score (mm)	0.0	69.8	22.10*	26.83*

SD, standard deviation; IQR, interquartile range; n, number.

was less comfortable and subsequently the speed was decreased to check if the selected speed was indeed the most comfortable.

After the participants had been equipped with the markers and electrodes for data collection, they walked on a split-belt treadmill (Bertec Corporation, Columbus, OH) under four different conditions in the following order: (1) a fixed normalized speed far below the preferred walking speed, (2) a fixed normalized speed lower than preferred, (3) preferred walking speed and (4) a fixed normalized speed higher than preferred, just below the transition to running. To be able to compare the kinematics between subjects, the speeds for conditions 1, 2 and 4 were normalized to leg length using the Froude number (Eq. 1).

$$FR = \frac{v^2}{g * l} \tag{1}$$

The Froude number normalizes the walking speed v to leg length l, with g, the gravitational acceleration. Leg length was measured from the greater trochanter to the ground. In the first condition, the Froude number was set to 0.0086, which reflects a walking speed of 0.28 m/s (1 km/h) for a Chinese male with average leg length [26]. For the second and fourth conditions, the Froude numbers were set to 0.063 and 0.252, reflecting speeds of 0.75 and 1.50 m/s (2.70 and 5.40 km/h, respectively) for an average Chinese male.

Data acquisition

Muscle activity, kinematics and ground reaction force were measured synchronously. Muscle activity of five trunk muscles was measured bilaterally using surface electromyography (EMG). The following muscles were measured: longissimus (LO), iliocostalis lumborum (IC), rectus abdominis (RA), external oblique (EO) and internal oblique (IO). The electrode locations were based on the SENIAM guidelines [27] and Anders et al. [28] (Table 2). Disposable bipolar electrodes (Ag-AgCl; 1 cm^2 recording area) were placed in the direction of the muscle fibres with 2 cm distance between the electrode centres and connected with pre-amplifiers and amplifiers (Motion Lab Systems, Inc., MA-300, Baton, Rouge LA). The reference electrodes, one for each EMG device, were placed on the anterior superior iliac spines (ASIS) on both sides. Before electrode placement, hair was removed and the skin was cleaned using alcohol. The data were amplified, online filtered with a high-pass filter at 5 Hz, and saved at 5,000 samples/s for further offline analysis.

Kinematic data were collected using Optotrak (Northern Digital Inc, Waterloo, ON, Canada) and were sampled at 100 samples/s. Six segments were recorded using cluster markers containing 3 LEDs, the lower and the upper leg on both sides, the pelvis and the thorax. The cluster markers were attached to straps around the legs, thorax and pelvis. To define the segments, three or four bony landmarks per cluster marker were identified [29]. For the lower legs, the

Table 2
Electrode orientation and position

Muscle (left and right)	Electrode orientation and position
M. longissimus (l/r)	Vertical, electrodes placed at 2 fingers width lateral from the L1 spinous process
M. iliocostalis lumborum(l/r)	In the direction of the line between the PSIS and most inferior point of rib 12, the electrodes need to be placed 1 finger width medial from the line from the PSIP to the lowest point of rib 12, at the level of L2
M. rectus abdominis (l/r)	Vertical, 4 cm lateral to umbilicus, caudal electrode at level of umbilicus, cranial above
M. external oblique (l/r)	Along the line from most inferior point of costal margin to opposite pubic tubercle, cranial electrode directly below most inferior point of rib 12
M. internal oblique(l/r)	Along horizontal line between both ASIS's, medial from inguinal ligament

PSIS, posterior superior iliac spine; ASIS, anterior superior iliac spine.

lateral and medial malleolus and the lateral and medial epicondyle were used. For the upper legs, the lateral and medial epicondyle and the greater trochanter defined the segment. The pelvis was defined using the right and left ASIS, the midpoint between the posterior superior iliac spine (PSIS) and the umbilicus, and the thorax with the xiphoid process, the suprasternal notch and the spinous processes of T6 and C7.

Ground reaction force data were also recorded, using the force plates (one for each belt) present in the treadmill, and were measured at the same frequency as the EMG, 5,000 samples/s.

Data analysis

All data analyses were performed using Matlab 2017b (MathWorks, Natick, Massachusetts, MA).

Gait cycle detection

For all conditions, a number of strides at the beginning and at the end of the trial was discarded, so that the number of strides that was analysed was equal for all participants. For the first to the fourth condition the middle 40, 60, 80 and 90 strides, respectively, were analysed. First, the initial contacts and toe offs were determined using the force plate according to the method of Roerdink et al. [30], and in addition kinematic data of the legs were used to distinguish between the left and right leg. These were then used to define the gait cycles from left heel strike to left heel strike and four phases of the cycle: first double support phase, single support phase of the left leg, the second double support phase and the single support phase of the right leg.

Kinematics

First, marker position time series were low-pass filtered at 5 Hz, with a fourth-order bi-directional Butterworth filter, whereafter the segment orientations were calculated. The axes were defined as follows: the x-axis was pointing in the forward/walking direction, the y-axis perpendicular to the x-axis to the left and the z-axis pointing upwards. Trunk and pelvis kinematics were both analysed around three axes, resulting in three angles for both segments. Trunk kinematics were determined relative to the pelvis and the pelvis relative to the global coordinate system. The local coordinate systems were aligned using a reference posture, where the participant stood straight with the feet together and arms next to the body with the palms of the hands facing forward.

The angle time series were split in n separate gait cycles using the initial contacts. Then all the time series were time normalized to the total gait cycle, using a 101-points spline interpolation, resulting in n vectors of 101 time points from 0% to 100% of the gait cycle. To calculate the stride-to-stride angle variability, the mean gait cycle pattern was calculated for every angle and subtracted from every stride, resulting in $n \times 101$ vectors of residuals. The mean of the absolute residual vectors was calculated resulting in 1×101 mean residuals vector. The stride-to-stride angle variability was defined as the mean of this 1×101 mean residuals vector.

EMG

The EMG was first band-pass filtered between 10 and 500 Hz using a second-order bi-directional Butterworth filter. The EMG signal was cleaned from ECG contaminations using the method described by Willigenburg et al. [31]. Since the channel of the left RA was heavily contaminated with electrocardiographic signal, this channel was used to remove electrocardiographic contamination from the other signals; therefore, the signal of the left RA was not used for further analysis. The linear envelope was obtained by rectifying the EMG and applying a fourth-order bi-directional low-pass Butterworth filter of 25 Hz.

Before calculating the muscle activation variability, the EMG data were normalized to the mean of the linear envelope of n strides. The normalized linear envelopes were split into separate gait cycles and time normalized to n vectors of 101 time points. The stride-to-stride muscle activation variability was calculated in the same way as the stride-to-stride angle variability. Data were averaged over left and right muscles, except for RA for which only the right side was analysed.

Statistical analysis

A factor analysis was conducted per speed to investigate interdependence of the dependent variables. The first three factors, explaining the largest part of the total variance, were examined to see if some variables consistently loaded on the same factor, which would mean that these variables are highly correlated. Moreover, the effect of speed on these interdependencies was examined. The factor analysis was executed in Matlab 2017b (MathWorks, Natick, Massachusetts, MA) using the function 'factoran' with a varimax rotation.

To compare the variability in kinematics and muscle activation between two groups based on fear of movement, two groups were defined with a median-split based on the TAMPA scores. The two patients with the median TAMPA-score were excluded from the analysis. This resulted in a low fear of movement (LOW) group with a score below 43 and a high fear of movement (HIGH) group with a score higher than 43. To test for differences between the two groups two mixed-design Multivariate Analyses of Variance (MANOVA) were conducted using SPSS 23.0 (IBM Corporation, Armonk, NY), one for the kinematic variability and one for the variability in muscle activation, with Speed as a within-subjects factor and Group (high vs low fear) as a between-subjects factor. Six and five variables were included, respectively, with two factors: two groups and four speed conditions. Also, the interaction effect between Group and Speed was analysed. In case of a significant Group effect, post hoc univariate ANOVAs were performed to test the differences between the groups

for every individual variable. For all statistics, the significance level was 0.05.

Results

There were no significant differences in anthropometric parameters (i.e., age, length, weight and body mass index) between the two groups. Also, the VAS-score and the duration of the pain were not significantly different between the groups. Three participants were not able to walk at all four speeds and were therefore excluded from the analysis. This resulted in a total of 26 patients, 13 in each group, with a TAMPA-score ranging from 32 to 42 for the LOW group and 44 to 56 for the HIGH group.

Fig. 1 shows the factor loadings on the first three factors from the factor analysis. The variability of the kinematics (the six variables on the left in each graph) and muscle activation (the five variables on the right in each graph) were consistently projected on different factors and this was clearer at higher speeds, indicating that variability of kinematics and variability of muscle activation present largely independent information. The variables quantifying kinematic variability loaded on the same factors at each speed. In most cases, the variables quantifying variability of muscle activation also loaded on the same factors. However, the variability of IO activation often (in the very slow, slow and fast speed) loaded on a different factor and the variability of the LO loaded on another factor at the preferred speed.

Neither the MANOVA for kinematic variability, nor for variability of muscle activation revealed significant Group effects (Hotelling's Trace F=0.237; 0.396, p=.959; .846, respectively). Speed significantly decreased kinematic variability and increased variability in muscle activation (Hotelling's Trace F=8.363; 4.495, p<.0001; <.0001, respectively). No significant interactions between Group and Speed were found (Hotelling's Trace F=0.204; 0.100, p=.762; .963, respectively). The results from the analyses and the differences between the groups with the 95% confidences intervals averaged over speed conditions are shown in Fig. 2.

Discussion

The aim of this study was to examine differences in variability of trunk kinematics and trunk muscle activation between two subgroups of LBP patients based on fear of movement. It was hypothesized that the group with more fear of movement would show less variability than the group with less fear of movement. The data did not support this hypothesis.

Our results indicated that there were no significant differences between the two groups, neither for kinematic, nor for muscle activation variability. So, based on these results fear of movement appears not to be associated with variability in kinematics and muscle activation.

Our results appear to be in contrast with findings of Karayannis et al. [18], who found a positive correlation between trunk stiffness and fear of movement and fear-

avoidance beliefs. Although in the current study stiffness was not estimated, no differences in variability of trunk and pelvic kinematics were found, which would be expected if trunk stiffness was different between the two groups [32,33]. However, it should be noted that Karayannis et al. [18] estimated trunk stiffness during a perturbation task. It could be that the knowledge of the impending perturbation affected trunk motor control differently in groups with different levels of fear of movement, while the walking task studied here was not threatening enough to cause a difference between the groups. Lamoth et al. [13] reported similar results as found in the current study; they found no correlation between fear of movement and variability of trunk kinematics and Erector Spinae activation during gait.

Literature has shown relationships between pain-related psychological factors and, for example, trunk stiffness and muscle activation [18,21]. Although different pain-related psychological factors, such as fear of movement, fear-avoidance beliefs and pain catastrophizing, are correlated [34], they are obviously not the same. Fear-avoidance beliefs and pain catastrophizing, or a composite score based on these concepts might be more predictive of changes in trunk motor control in LBP compared to fear of movement.

Another explanation for the lack of group differences could be found in the patient population that was recruited in this study. Patients were recruited at the Shanghai Jiaotong University, Affiliated Sixth People's Hospital in China. In China, patients often go immediately to the hospital without consulting a general practitioner. Therefore, it could be that the patients in this study did not suffer from severe LBP and therefore had not acquired a distinctive coping strategy. Thus, it could be that studying another patient population would result in more distinctive differences. Also, the classification into high and low fear of movement, based on a median-split, may not have yielded enough contrast. Fig. 3 shows that the dataset, used for the final analysis, did not include many patients with scores at the low and high end of the TAMPA-scale. With a larger sample size and more participants at the high and low ends of the TAMPA-scale, grouping based on, for example, quartiles would be possible, to obtain a larger contrast between the groups. However, when the current participant group was split in three groups, and the group with the highest and the lowest TAMPA-scores were compared, no clear different results were found. Besides, when inspecting Fig. 2, it can be seen that the variability, especially of the kinematics, tended to be higher in the HIGH group compared to the LOW group. Therefore, it is not likely that increasing the sample size would lead to results that would support our original hypothesis.

Based on previous literature [13] and the current study, it seems that the variability in kinematics and muscle activation during walking is not associated with fear of movement. Patients with LBP have been shown to display reduced kinematic variability and this has been interpreted as behaviour adapted under the influence of fear of pain or re-injury
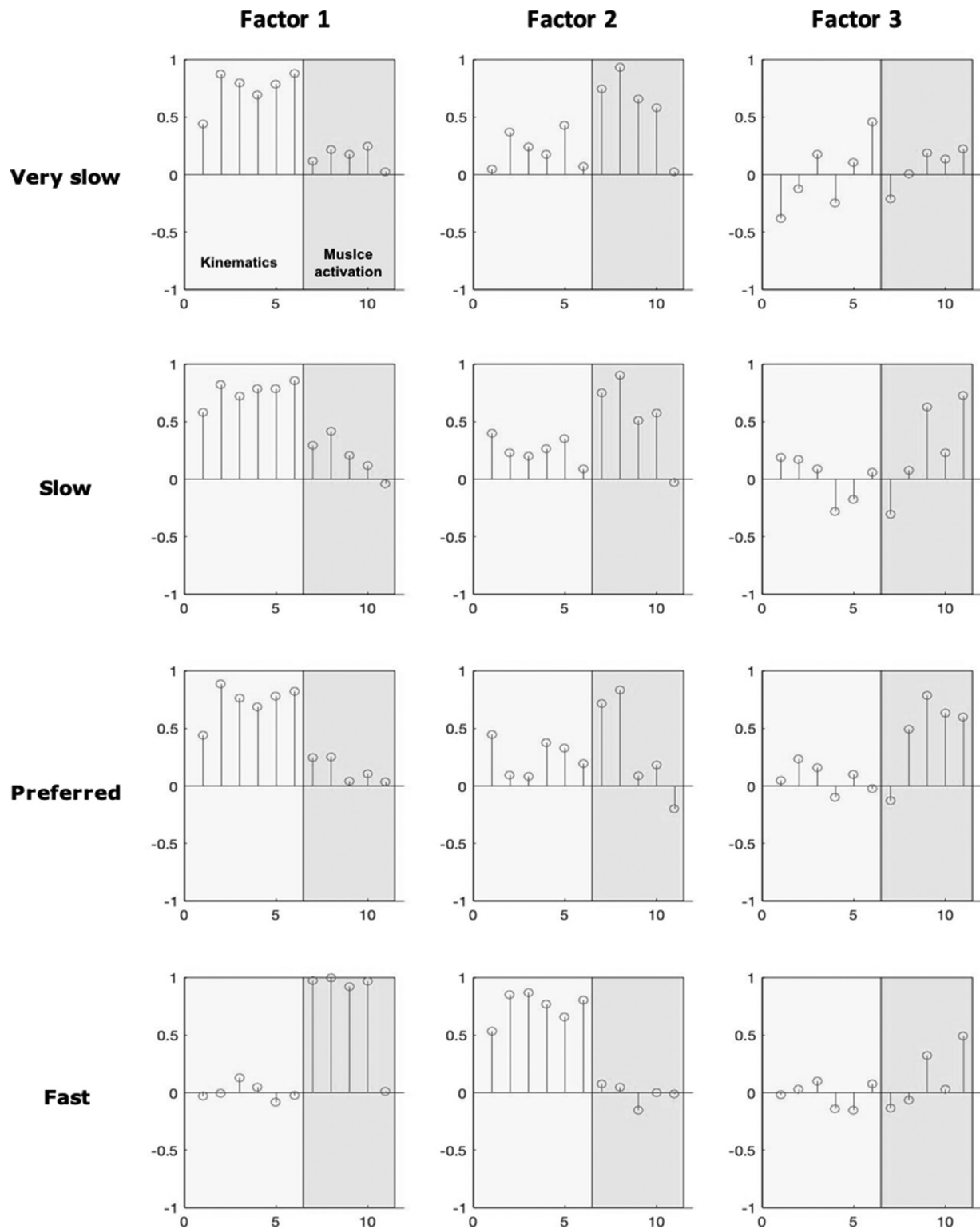
Fig. 1. Factor loadings. Shows the factor loadings on the first three factors from the factor analysis for the four different walking speeds. The left sides of each graph (light shading) represent the six variables quantifying kinematic variability and the right sides (dark shading) the variables quantifying variability in muscle activation. Variability variables corresponding to figure labels : (1) flexion trunk, (2) lateral flexion trunk, (3) rotation trunk, (4) posterior tilt pelvis, (5) lateral tilt pelvis, (6) rotation pelvis, (7) longissimus, (8) iliocosalis, (9) rectus abdominus, (10) external oblique and (11) internal oblique.

potentially leading to adverse consequences [17]. This would suggest a cognitive-behavioural approach perhaps combined with motor control exercise, to achieve a more variable motor behaviour. However, the current results do not support the role of fear in reducing kinematic variability and hence would not support such an approach. We note here that trunk
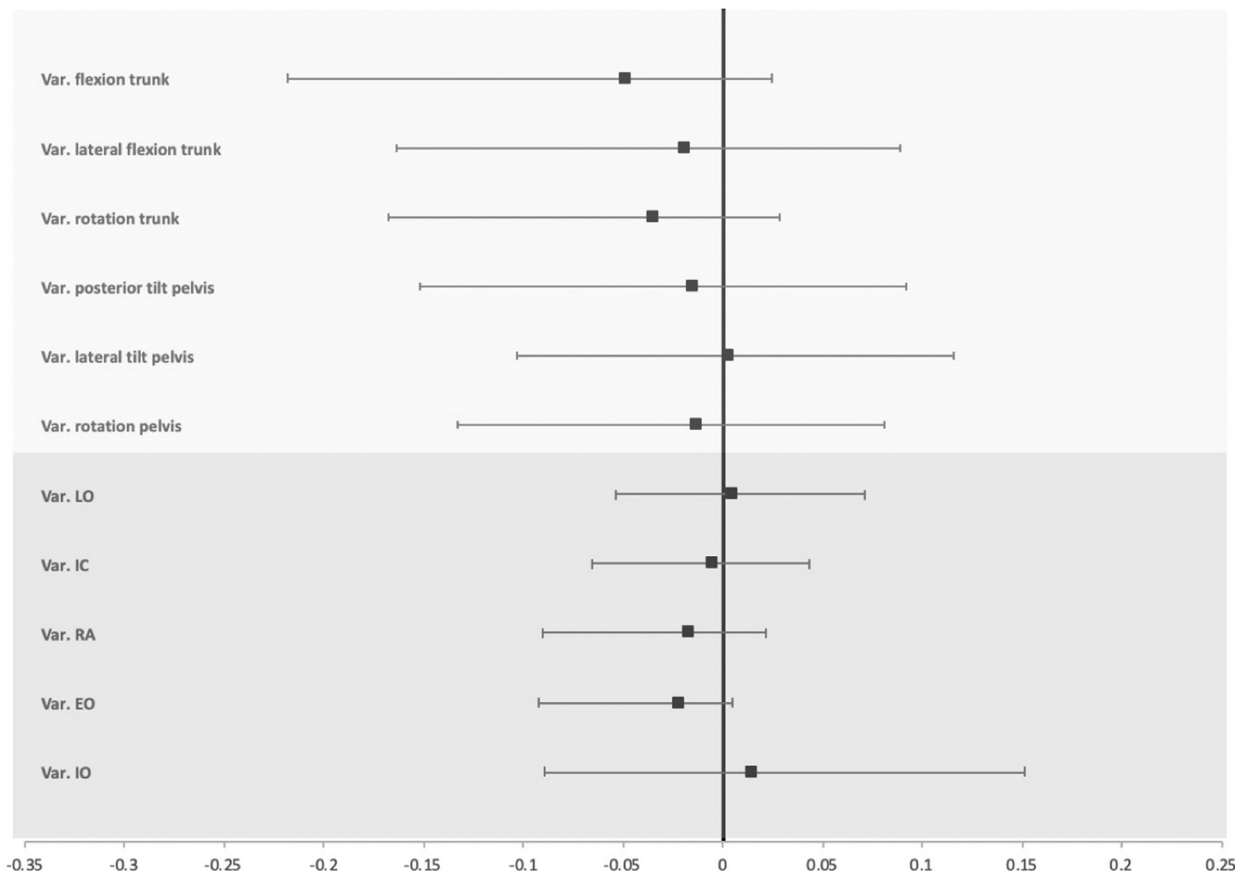
Fig. 2. Low vs high. Mean differences between the HIGH and the LOW groups for all variables (black squares) and their 95% confidence intervals calculated as LOW-HIGH. All differences are scaled to the total range of each variable. Var., variability; LO, longissimus; IC, iliocostalis lumborum; RA, rectus abdominus; EO, external oblique; IO, internal oblique. The top of the graph (light shading) represents the six variables quantifying kinematic variability and the bottom (dark shading) the variables quantifying variability in muscle activation.

stiffness and movement variability might be differently associated with fear of movement in motor task that impose a larger threat. Therefore, future studies should be devoted to investigate the variability in motor tasks that are more challenging and possibly more influenced by fear of movement. Hereby, either more evidence can be obtained for the absence of an association between fear of movement and variability in LBP patients, or such studies could confirm the existence of fear of movement-based subgroups.

The factor analysis gave an interesting insight in the relationship between variability of kinematics and the variability of muscle activation. The results indicate that variability of the included muscles is not correlated to the variability of pelvis and spine kinematics, this was clearest at the fast speed. This might be due to co-contraction, or due to the fact that more muscles contribute to trunk movement than the muscles that were included. This is in contrast with Gabriel et al. [35] who found associated changes in variability of
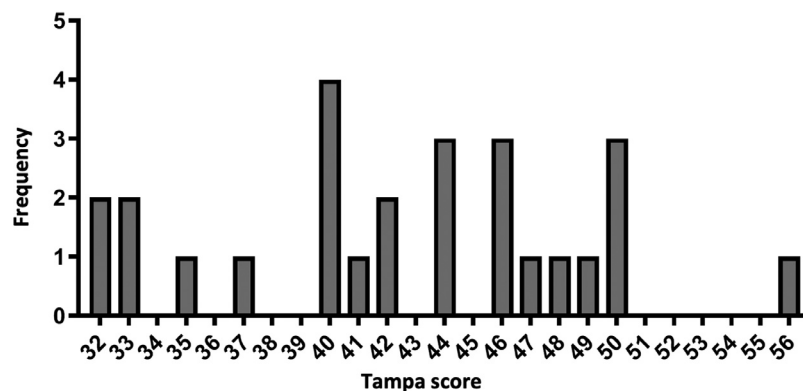

Fig. 3. TAMPA-score distribution. The frequency of Tampa scores within the dataset of 26 patients used for the analysis.

elbow kinematics and biceps and triceps both decreased during an elbow flexion task. These differences may be due to the difference in complexity of the task, joint geometry and the number of muscles around the joint. Fewer muscles are involved in elbow control than in trunk control. In addition, trunk kinematic variability in gait will be affected by variability in leg and arm movements. It should be noted that for the factor analysis relatively many variables were included with respect to the number of participants. However, the factor scores were only used to show the relationship between the different variability measures and were not used in any further analyses.

The lack of correlation between kinematic variability and variability in muscle activation is important for the analyses in future studies. Results obtained at the level of muscle activity will not be representative for results at the kinematic level and vice versa. Furthermore, it implies that differences between groups may average out if the variability is analysed as a single construct.

Some limitations of this study should be addressed. First of all, unfortunately we were not able to reach the target sample size and ended up with a sample size of 26. Moreover, the correlation between the repeated measures was 0.59. A post hoc analysis of the achieved power resulted in a power of 0.65, indicating a possible lack of power. However, when studying Fig. 2, one can see that the results tend to point in the opposite direction than hypothesized. Therefore, increasing the sample size did not seem warranted as it would not likely alter conclusions. Secondly, few men signed up as a volunteer, as a result more women than men were included. However, since the men and women were more or less equally distributed over the two groups, this should not have caused any bias. Lastly, not all participants had experience with walking on a treadmill. In those cases, participants received further instructions and the familiarization trial was extended until they felt comfortable. All participants were able to walk comfortably after the familiarization trial. Besides, treadmill walking has been reported to result in altered trunk and pelvis kinematics [36], although, others found few differences between treadmill and normal walking [37]. In this study, however, this cannot lead to bias as all trials were performed in treadmill walking. At last, two of the authors received financial support for conducting this study; however, this was funding from governmental organisations. These organisations had no interference in the study design or execution of this study.

Conclusions

The results of this study do not support the hypothesis that fear of movement is associated with variability in kinematics and muscle activation during gait in LBP patients. Variability in trunk kinematics was largely independent from variability in trunk muscle activation. Variability of kinematics and muscle activation should be studied separately and identification of the sources of variability of trunk movement appears warranted.

References

[1] Hoy D, March L, Brooks P, Blyth F, Woolf A, Bain C, et al. The global burden of low back pain: estimates from the global burden of disease 2010 study. Ann Rheum Dis 2014;73:968–74 https://doi.org/10.1136/annrheumdis-2013-204428.

[2] NIH. Low back pain. 2014 https://doi.org/10.1098/rspb.2006.3477.

[3] Dubois JD, Abboud J, St-Pierre C, Piché M, Descarreaux M. Neuromuscular adaptations predict functional disability independently of clinical pain and psychological factors in patients with chronic nonspecific low back pain. J Electromyogr Kinesiol 2014;24:550–7 https://doi.org/10.1016/j.jelekin.2014.04.012.

[4] Byström MG, Rasmussen-Barr E, Johannes W, Grooten A, Grooten WJA. Motor control exercises reduces pain and disability in chronic and recurrent low back pain: a meta-analysis. Spine (Phila Pa 1976) 2013;38:350–8 https://doi.org/10.1097/BRS.0b013e31828435fb.

[5] Macedo LG, Maher CG, Latimer J, McAuley JH. Motor control exercise for persistent, nonspecific low back pain: a systematic review. Phys Ther 2009;89:9–25 https://doi.org/10.2522/ptj.20080103.

[6] Saragiotto BT, Maher CG, Yamato TP, Costa LOP, Menezes Costa LC, Ostelo RWJG, et al. Motor control exercise for chronic non-specific low-back pain. Cochrane Database Syst Rev 2016;2016 https://doi.org/10.1002/14651858.CD012004.

[7] van Dieën JH, Reeves NP, Kawchuk G, van Dillen L, Hodges PW. Motor control changes in low-back pain: divergence in presentations and mechanisms. J Orthop Sports Phys Ther 2018:1–24 https://doi.org/10.2519/jospt.2019.7917.

[8] Mazaheri M, Coenen P, Parnianpour M, Kiers H, van Dieën JH. Low back pain and postural sway during quiet standing with and without sensory manipulation: a systematic review. Gait Posture 2013;37:12–22 https://doi.org/10.1016/j.gaitpost.2012.06.013.

[9] Laird RA, Gilbert J, Kent P, Keating JL. Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. BMC Musculoskelet Disord 2014;15:229 https://doi.org/10.1186/1471-2474-15-229.

[10] van Dieën JH, Cholewicki J, Radebold A. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. Spine (Phila Pa 1976) 2003;28:834–41 https://doi.org/10.1080/10494820.2015.1113709.

[11] Prins MR, Griffioen M, Veeger TTJ, Kiers H, Meijer OG, van der Wurff P, et al. Evidence of splinting in low back pain? A systematic review of perturbation studies. Eur Spine J 2018;27:40–59 https://doi.org/10.1007/s00586-017-5287-0.

[12] Vogt L, Pfeifer K, Portscher M, Banzer W. Influences of nonspecific low back pain on three-dimensional lumbar spine kinematics in locomotion. Spine (Phila Pa 1976) 2001 https://doi.org/10.1097/00007632-200109010-00019.

[13] Lamoth CJC, Meijer OG, Daffertshofer A, Wuisman PIJM, Beek PJ. Effects of chronic low back pain on trunk coordination and back muscle activity during walking: Changes in motor control. Eur Spine J 2006;15:23–40 https://doi.org/10.1007/s00586-004-0825-y.

[14] Lamoth CJC, Meijer OG, Wuisman PIJM, van Dieën JH, Levin MF, Beek PJ. Pelvis-thorax coordination in the transverse plane during walking in persons with nonspecific low back pain. Spine (Phila Pa 1976) 2002;27:E92–9 https://doi.org/10.1097/00007632-200202150-00016.

[15] Lamoth CJC, Stins JF, Pont M, Kerckhoff F, Beek PJ. Effects of attention on the control of locomotion in individuals with chronic low back pain. J Neuroeng Rehabil 2008;5:13 https://doi.org/10.1016/j.appet.2013.11.003.

[16] van den Hoorn W, Bruijn SM, Meijer OG, Hodges PW, van Dieën JH. Mechanical coupling between transverse plane pelvis and thorax rotations during gait is higher in people with low back pain. J Biomech 2012;45:342–7 https://doi.org/10.1016/j.jbiomech.2011.10.024.

[17] Van Dieën JH, Flor H, Hodges PW. Low-back pain patients learn to adapt motor behavior with adverse secondary consequences. Exerc Sport Sci Rev 2017;45:223–9 https://doi.org/10.1249/JES.0000000000000121.

[18] Karayannis NV, Smeets RJEM, van den Hoorn W, Hodges PW. Fear of movement is related to trunk stiffness in low back pain. PLoS One 2013;8:e67779 https://doi.org/10.1371/journal.pone.0067779.

[19] Hedayati R, Kahrizi S, Parnianpour M, Bahrami F, Kazemnejad A, Mobini B. The study of the variability of anticipatory postural adjustments in patients with recurrent non-specific low back pain. J Back Musculoskelet Rehabil 2014;27:33−40 https://doi.org/10.3233/BMR-130416.

[20] Pakzad M, Fung J, Preuss R. Pain catastrophizing and trunk muscle activation during walking in patients with chronic low back pain. Gait Posture 2016;49:73−7 https://doi.org/10.1016/j.gaitpost.2016.06.025.

[21] Massé-Alarie H, Beaulieu LD, Preuss R, Schneider C. Influence of chronic low back pain and fear of movement on the activation of the transversely oriented abdominal muscles during forward bending. J Electromyogr Kinesiol 2016;27:87−94 https://doi.org/10.1016/j.jelekin.2016.02.004.

[22] van der Hulst M, Vollenbroek-Hutten MM, Schreurs KM, Rietman JS, Hermens HJ. Relationships between coping strategies and lumbar muscle activity in subjects with chronic low back pain. Eur J Pain 2010;14:640−7 https://doi.org/10.1016/j.ejpain.2009.10.011.

[23] Hiscock M. Comment on C. M. Clark, L. Lawlor-Savage, & V. M. Goghari. Measurement 2016;14:64−6 https://doi.org/10.1007/s10512-017-0253-9.

[24] Wei X, Xu X, Zhao Y, Hu W, Bai Y, Li M. The Chinese version of the Tampa Scale for Kinesiophobia was cross-culturally adapted and validated in patients with low back pain. J Clin Epidemiol 2015;68:1205−12 https://doi.org/10.1016/j.jclinepi.2015.07.003.

[25] Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods 2007;39:175−91 https://doi.org/10.3758/BF03193146.

[26] Lin YC, Wang MJJ, Wang EM. The comparisons of anthropometric characteristics among four peoples in East Asia. Appl Ergon 2004;35:173−8 https://doi.org/10.1016/j.apergo.2004.01.004.

[27] Hermens HJ, Freriks B, Merletti R, Stegeman DF, Blok J, Rau G, et al. European recommendations for surface electromyography, results of the SENIAM Project. Roessingh Res Dev bV 1999;8:13−54.

[28] Anders C, Scholle H-C, Wagner H, Puta C, Grassme R, Petrovitch A. Trunk muscle co-ordination during gait: relationship between muscle function and acute low back pain. Pathophysiology 2005;12:243−7 https://doi.org/10.1016/j.pathophys.2005.09.001.

[29] Della Croce U, Cappozzo A, Kerrigan DC. Pelvis and lower limb anaomical landmark calibration precision and its propogation to bone geometry and joint angles. Med Biol Eng Comput 1999;37:155−61 https://doi.org/10.1007/BF02513282.

[30] Roerdink M, Coolen (H) B, Clairbois BHE, Lamoth CJC, Beek PJ. Online gait event detection using a large force platform embedded in a treadmill. J Biomech 2008;41:2628−32 https://doi.org/10.1016/j.jbiomech.2008.06.023.

[31] Willigenburg NW, Daffertshofer A, Kingma I, van Dieën JH. Removing ECG contamination from EMG recordings: a comparison of ICA-based and other filtering procedures. J Electromyogr Kinesiol 2012;22:485−93 https://doi.org/10.1016/j.jelekin.2012.01.001.

[32] Shiller DM, Laboissière R, Ostry DJ. Relationship between jaw stiffness and kinematic variability in speech. J Neurophysiol 2002;88:2329−40 https://doi.org/10.1152/jn.00286.2002.

[33] Selen LPJ, Beek PJ, Van Dieën JH. Can co-activation reduce kinematic variability? A simulation study. Biol Cybern 2005;93:373−81 https://doi.org/10.1007/s00422-005-0015-y.

[34] George SZ, Calley D, Valencia C, Beneciuk JM. Clinical investigation of pain-related fear and pain catastrophizing for patients with low back pain. Clin J Pain 2011;27:108−15 https://doi.org/10.1097/AJP.0b013e3181f21414.

[35] Gabriel DA. Changes in kinematic and EMG variability while practicing a maximal performance task. J Electromyogr Kinesiol 2002;12:407−12 https://doi.org/10.1016/S1050-6411(02)00026-3.

[36] Vogt L, Pfeifer K, Banzer W. Comparison of angular lumbar spine and pelvis kinematics during treadmill and overground locomotion. Clin Biomech 2002;17:162−5 https://doi.org/10.1016/S0268-0033(01)00111-5.

[37] Okello MM. Tourism & hospitality economic contribution, challenges and way forward for wildlife-based tourism industry in Eastern African Countries. Toursim Hosp 2014;3:1−12 https://doi.org/10.1016/j.future.2017.05.027.