Deterministic accessory spinal movement in functional tasks characterizes individuals with low back pain

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Objectives: To apply a novel method to assess the characteristics of spinal movement in subjects with low back pain (LBP) in a functional task.

Methods: 17 subjects suffering from chronic non-specific LBP (average pain intensity: 1.8 ± 1.6), and 17 age and gender matched controls performed a repetitive lifting task. Spinal movement was recorded using a novel sensor strip with 12 angle sensors recording the spinal dynamics in evenly spaced (25 mm) locations along the spine. Recurrence quantification analysis was applied to different components of the angles to assess the structure of its variability.

Results: Mechanically, the LBP and control group performed the task similarly. Reported pain increased in the LBP group, yet task-related angular movement was not different. However, the percentage of determinism for the accessory angular movement (movement variability not directly related to task execution) was significantly higher for the LBP group, indicating a more deterministic (less random) structure of the muscle activation pattern variability.

Conclusion: The structure of the variability of spinal movement differs in subjects with chronic non-specific LBP.

Significance: The determinism of accessory spinal movement may be a useful measure for evaluation of movement impairment in LBP and for monitoring rehabilitation effects.

1. Introduction

Low back pain (LBP) is a common disorder affecting the majority of people during their lifetime (Dunn and Croft, 2004; Kent and Keating, 2005; Hoy et al., 2010). The chance of recurrence is high, and in many cases the pain is never fully resolved (Kent and Keating, 2005; Hoy et al., 2010). Thus LBP implies functional impairment for a large proportion of the population and imposes large demands on health and social systems (Dunn and Croft, 2004).

People with chronic LBP display a variety of biomechanical disturbances. Such disturbances include altered hip-trunk coordination (Lamoth et al., 2002; Shum et al., 2007), decreased spinal range of motion (Shum et al., 2007; Silfies et al., 2009), and longer time to regain stability following perturbations (Mok et al., 2011). These biomechanical differences may in part be attributed to abnormal muscle recruitment patterns (Roy et al., 1997; Hodges and Richardson, 1999; Humphrey et al., 2005) and decreased ability to modulate proprioceptive feedback gain according to task requirements (Claeys et al., 2011). The influence of LBP on the...
magnitude of movement variability, however, is less clear. For example, trunk movement in gait has been reported to increase (Vogt et al., 2001) and to decrease (Lamoth et al., 2008; Van Den Hoorn et al., 2011). Furthermore, postural sway has been reported to be higher (Leinonen et al., 2003), unchanged (Van Dieën et al., 2010), and to either de- or increase depending on the stability of the support (Claeys et al., 2011). Finally, the onset of trunk muscle activity in repetitive arm movements is less variable for persons with LBP (Jacobs et al., 2009), whereas the trunk muscle EMG activity displays higher variability during gait (Lamoth et al., 2006). In particular during slow movements, little difference has been found between persons with and without LBP (Hodges and Richardson, 1999; Lamoth et al., 2006).

Instead, recent studies have suggested that the mechanical differences related to LBP may reside in the intrinsic structure of the variability, rather than in its magnitude (Lamoth et al., 2006; Silfies et al., 2009). For example, using principal component analysis, Lamoth and colleagues (2006) showed that lumbar spine movement was less coordinated in persons with LBP than in healthy controls.

In this study, we investigated the variability of spinal movements during a repetitive functional task using novel angle sensor strips that allowed measurement of angular trajectories in 12 evenly spaced locations along the spine (Consmüller et al., 2012). With this method, the spinal dynamics could be analyzed in greater detail than has previously been possible. For each of the spinal angles, the variability was analyzed with respect to the dynamics related to the execution of the task as well as to the accessory dynamics reflecting the random variability occurring during the movements. Recurrence Quantification Analysis (RQA), a methodology allowing quantification of recurrent patterns in non-stationary data (Eckmann et al., 1987), was employed for the analysis of the structure of the variability. RQA has previously been applied within biomechanical analyses (Riley et al., 1999; Labini et al., 2012). We hypothesized that the differences between the LBP group and the controls would be found not in the magnitude of variability by which the task was executed, but instead in the structure of this variability.

2. Methods

2.1. Subjects

Seventeen age and gender matched healthy subjects were recruited to act as the control group. These pain-free subjects were included if they had no relevant history of back or lower limb pain or injury that limited their function and/or required treatment from a health professional. Patients and control subjects had to have the capacity to give their consent at their own will. Participants were excluded from both groups if they had any major circulatory, neurological, or respiratory disorders, recent or current pregnancies, previous spinal surgery, current treatment for LBP from health care providers, or participation in specific trunk muscle exercise in the past 3 months. Subjects were also excluded from both groups if they were taking any medication such as opioids, anticonvulsants, or antidepressants. Patients taking non-steroidal anti-inflammatory drugs (NSAIDs) on a regular basis were also excluded and patients were asked not to take any NSAID or simple analgesics on the day of the experiment. Initial screening was conducted over the telephone and eligible persons attended a baseline evaluation appointment.

Ethical approval for the study was granted by the local Ethics Committee and the procedures were conducted according to the Declaration of Helsinki. The study was performed at the Department of Neurorehabilitation Engineering, Göttingen, Germany where all data was collected. The raw data was extracted and provided by Epionics Medical GmbH (Potsdam, Germany). All further analysis and writing of the manuscript were performed by the authors.

2.2. Questionnaires

A questionnaire was administered to obtain information on subject demographics, history, duration of pain, average intensity of pain and localization of pain in the LBP group. Patients completed the German version (Nigbur et al., 2009) of the Tampa Scale for Kinesiophobia (17 items; (Vlaeyen et al., 1995)), a measure to assess fear-avoidance behavior and fear-avoidance beliefs and the German version (Meyer et al., 2008) of the Pain Catastrophizing Scale (PCS), a measure of catastrophic thinking related to pain. The PCS is a 13-item questionnaire in which respondents rate the frequency with which they experience different thoughts and feelings when in pain (Osman et al., 1997). The German Oswestry Disability Index (ODI) (Mannion et al., 2006) was used to assess pain-related disability specifically related to LBP (10 items; (Fairbank and Pynsent, 2000)). Finally, the LBP group completed the German version of the Short Form of the Spielberger State-Trait Anxiety Inventory (SF-STAI) (Laux et al., 1981). It is a six-item questionnaire that has been shown to be a reliable and sensitive measure of anxiety (Spielberger et al., 1970). All subjects completed the German version (Bullinger, 1995) of the SF-36 Health Survey (Brazier et al., 1992), a measure of general health status.

Finally, the activity-related pain was monitored during the repetitive task. For this, subjects of both groups were asked to verbally rate their level of perceived pain intensity on an 11 point numerical rating scale (NRS) anchored with “no pain” (0) and “the worst possible pain imaginable” (10) at rest and every 40 s during the lifting task. Pain intensity was also noted 3 min after completion of the task.

Fig. 1. The functional task consisted of lifting a box containing a 5 kg weight between two shelves represented by box height and speed during the 8 s duration (A). The Epionics SPINE sensor system consists of two sensor strips each with 12 evenly spaced angle sensors (25 mm apart from one another). Due to the purely sagittal nature of the task the right one was considered representative. The bottom of the strip was located at the posterior superior iliac spine (PSIS).
3. Experimental procedure

As illustrated in Fig. 1A, subjects were asked to repetitively move a box (40 x 20 x 30 cm) with hole-shaped handles, loaded with a weight of 5 kg, between two shelves placed approximately at knee (lateral epicondyle of femur with the knee extended) and shoulder (position of the clavicle while standing) height. An absolute weight was selected rather than a relative weight to better represent a functional task that may be encountered by the subjects. The weight was placed in the center of the box and kept in position by means of light packaging foam. Starting from the lower shelf, the subjects were instructed to lift the box to the upper shelf in one second, wait for three seconds (without interrupting contact with the box), move it back to the lower shelf (in one second) and wait three seconds before commencing the next cycle. The task was performed to the beat of an electronic metronome and lasted for approximately three minutes (22 cycles were performed in total). The first and last cycle were discarded. Subjects practiced the movement sequence for ~1 min without the weight prior to data recording.

3.1. Movement analysis

Motion of the spine was assessed using Epionics SPINE (Epionics Medical GmbH, Potsdam, Germany). The SPINE system is composed of two strips, both equipped with 12 angle sensors per strip, as shown in Fig. 1B. The SPINE system measures angles in the sagittal plane at a rate of 50 Hz.Sensor strips were placed 5 cm laterally to the spine by means of adhesive bandages. In this study, the angle data from one of the sensor strips (right side) was used. The most caudal sensor was aligned with subject’s posterior superior iliac spine (Consmüller et al., 2012). Recorded data from this sensor will be referred to as spinal angle #1, while data from consecutively more cranial sensors will be referred to as spinal angle #2–12. Variance and offset (average value) of each spinal angle were quantified.

3.2. Data analysis

The recorded angles were low-passed filtered at 4 Hz (2nd order butterworth) to remove recording noise. This will henceforth be referred to as the task-related angular trajectory. Next, notch filters (3rd order, Q-factor = 2) were applied at the center movement frequency (peak power frequency in the band 0.11–0.14 Hz) and its 10 first harmonics to remove the components of the angular trajectories directly reflecting the voluntary execution of the task. This will henceforth be referred to as the accessory angular trajectory. RQA as well as the calculation of the variance of the angles were performed on task-related as well as the accessory angular trajectory.

The procedure of RQA has been described in detail elsewhere (Eckmann et al., 1987) and will only be briefly summarized here. Using the entire duration of the data, the phase-space matrix was constructed with 5 embedded dimensions and with a time-lag 200 ms, as recommended by the comprehensive analysis of optimal RQA parameter settings when applied to center of pressure data performed by Hasson et al. (Hasson et al., 2008). Next, the distance matrix was calculated as the Euclidean distance between the rows of the phase-space matrix. Finally, the binary recurrence space was computed by comparing the entries of the distance matrix to a threshold (below threshold: 1; above threshold: 0). This threshold was set to 10% of the average distance, which is within the range of values utilised in previous studies in which RQA was applied to biomechanical data including, for example, inertial measurements during gait (Riley et al., 1999; Schmit et al., 2006; Hasson et al., 2008; Labini et al., 2012). The percentage of determinism (%DET) was calculated as the ratio between the number of pixels in the recurrence space with the value 1 lying on diagonal lines (2 or more pixels) and the total number of pixels with the value 1.

Furthermore, for the LBP group, %DET was also estimated in 4 evenly sized, non-overlapping windows (40 s) to allow comparison with the instantaneous perceived pain intensity ratings. Here, the average %DET of all sensors for each patient was used for each of the four time intervals. %DET and perceived pain intensity was expressed as a difference from baseline.

3.3. Statistical analysis

Percentages of determinism and angular variances for the angles recorded from each sensor were compared across groups using student’s t-test while the perceived pain intensities were compared using F-test. Linear regression was applied to investigate the correlation between the percentage of determinism and the perceived pain intensity. The level of significance was set to 0.05.

4. Results

4.1. Pain intensity

Baseline characteristics of the LBP and control groups are presented in Table 1. At the beginning of the experiment the subjects of the LBP group rated their current pain intensity as 1.8 ± 1.5. Pain increased during performance of the repetitive task (F = 5.1, p < 0.001) by 120 and 160 s relative to baseline (NRS: 2.5 ± 2.6 at 160 s), however current pain intensity had returned to baseline values 3 min after completion of the task (Fig. 2). Control subjects reported no pain at rest or throughout the repetitive lifting task.

4.2. Spinal angles

Fig. 3 depicts the task-related and accessory angular trajectories and their Fourier spectrums for one angle (sensor #5) of one representative subject of the LBP group. The repetitive timing of the task is clearly visible as distinct spectral peaks in the spectrum of the task-related angular trajectory (Fig. 3B). There was no significant difference between the angular offset (mean angle for each sensor throughout entire recording; average p-value = 0.54, lowest p-value = 0.18 for sensor #2) or the within-group variance of the angular offset across the 12 sensors for the two groups (p = 0.27). The variability of the task-related angular trajectory was several magnitudes larger than the accessory angular trajectory.

Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>LBP</th>
<th>Control</th>
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<tbody>
<tr>
<td>Age (yrs)</td>
<td>32.5 ± 9.6</td>
<td>29.7 ± 7.3</td>
</tr>
<tr>
<td>Gender (% male)</td>
<td>41</td>
<td>47</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>177.4 ± 9.6</td>
<td>174.8 ± 10.3</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>743 ± 12.8</td>
<td>692 ± 14.0</td>
</tr>
<tr>
<td>Duration of pain (months)</td>
<td>34.2 ± 29.3</td>
<td></td>
</tr>
<tr>
<td>Average pain intensity</td>
<td>3.1 ± 2.2</td>
<td></td>
</tr>
<tr>
<td>Oswestry disability score (ODI: 0–100 (%))</td>
<td>14.2 ± 7.2</td>
<td></td>
</tr>
<tr>
<td>SF-36 (total) (0–100)</td>
<td>66.9 ± 12.2</td>
<td>89.0 ± 6.0</td>
</tr>
<tr>
<td>Physical (0–100)</td>
<td>60.9 ± 14.2</td>
<td>89.2 ± 4.9</td>
</tr>
<tr>
<td>Mental (0–100)</td>
<td>67.6 ± 14.1</td>
<td>83.8 ± 5.4</td>
</tr>
<tr>
<td>TSK (17–68)</td>
<td>31.8 ± 5.9</td>
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</tr>
<tr>
<td>PCS (0–52)</td>
<td>16.1 ± 8.5</td>
<td></td>
</tr>
<tr>
<td>STAI (20–80)</td>
<td>40.2 ± 7.1</td>
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trajectory, and was highest for the most caudal sensors (Fig. 4). There was no difference in the magnitude of the task-related angles between the LBP and the control groups (Fig. 4A), indicating that the occurrence of back pain did not modify the execution of the task mechanically. Furthermore, there was little difference in the magnitude of the accessory angles between the LBP and the control group (only significantly different for accessory angles at sensor #2; \( p = 0.048 \); Fig. 4B).

4.3. Recurrence quantification analysis

Fig. 5 shows the estimated values of %DET (see Section 2– data analysis for detailed methodological description) for each sensor of the sensors for the LBP and control group respectively. When considering the task-related angular trajectory (Fig. 5A), there was little difference between the two groups. Only for one sensor (#10) the %DET was higher for the LBP group (\( p = 0.048 \)). Generally, the values of %DET were very high for both groups (99.83% and 99.87% for controls and patients respectively) reflecting the high level of repeatability of the task. The highest values were observed for the most caudal sensors (#1–#3) which also exhibited the

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Fig. 2. Change in pain intensity (NRS) with respect to baseline during the task (0–180 s) and after 3 min of rest after the completion of the task (360 s) for the LBP group.

Fig. 3. The task-related (non-notch-filtered; black) and the accessory (notch-filtered; grey) angles for spinal segment 5 for one representative LBP subject during 30 s of the task (A) and its fourier transform (B). Due to truncation of the y-axis, the spectral peaks of the non-notch filtered angles at the 0.13 Hz (amplitude: 6760) and 0.26 Hz (amplitude: 2828) are not included on the graph.

Fig. 4. The variance of the task-related (non-notch-filtered) (A) and the accessory (notch-filtered) (B) spinal segment angles for the control (circles) and LBP (triangles) groups. *Indicates significant difference (\( p < 0.05 \)).
highest angular deviations during the task (Fig. 4A). This correlation likely indicates that the forward bending movement was largely achieved by the lower spinal segments. Therefore, the angles at these segments were more deterministic in their nature, whereas movement at higher spinal segments may reflect stabilizing components of spinal movement. Contrary to the task-related angles, there was a large difference between the LBP and control groups for the accessory angular trajectories (Fig. 5B). Across all sensors, the %DET was higher for the LBP group (statistically significant in 8 of 12 sensors).

For subjects in the LBP group, the difference in %DET estimated in the 40 s windows of the accessory angular trajectories with respect to baseline tended to be positively correlated with the change in instantaneous perceived pain intensity (r = 0.23) with respect to pre-task level, but this relation was not statistically significant (p = 0.11). The %DET did not correlate with any other clinical features.

5. Discussion

In this study we investigated the impact of LBP on the mechanical actions of the back during execution of a repetitive, functional task. A novel sensor strip was applied, allowing accurate detection of changes in angles in 12 evenly spaced locations along the spine. Compared to the control group, no differences in angular offsets or the angular variability were found. Instead, the main finding was that the structure of the variability of the accessory (non-task related) movement across all measured spinal segments was less random, as indicated by a higher percentage of determinism, for subjects suffering from LBP. The accessory angular dynamics of the task was obtained by filtering out the frequencies related to the task. This was possible since the timing of the task was closely controlled using a metronome. In this way, the accessory angular dynamics represented the involuntary variability related to the execution of all types of movements, reflecting noise in the coordination of the activity of the involved muscles.

The baseline resting pain rating of the LBP subjects (NRS: 1.8 ± 1.5) was relatively low, but increased by 38% during the task (Fig. 2). Given the relatively short duration of the task applied in the study (3 min), it is likely that larger increases in pain would have occurred with extended periods of repetitive activity common to many occupational activities. Despite the presence of pain, there was no difference in the magnitude of the task-related angles between the LBP and control groups, indicating that the occurrence of back pain did not interfere with the ability of the subjects to correctly execute the exercise. This may in part be explained by the high level of standardization of the task (subjects were following the beat of the metronome indicating the timing of each step of the task). However, previous findings of pain-related mechanical changes in comparable tasks were all observed at higher baseline pain rating levels (baseline average VAS range: 3–6) (Esola et al., 1996; McClure et al., 2006; Hasson et al., 2008, 2009). On the other hand, more subtle, non-mechanical changes (e.g., the muscle recruitment pattern) have been observed for subjects at pain rating levels comparable to those in the current study (Thomas et al., 2007; Jacobs et al., 2009). Such observations may be a result of the same pain-related adaptations in muscle activation patterns that is reflected by changes in %DET in this study.

In this study we applied RQA to investigate the structure of the recorded spinal angles. Unlike traditional spectral analysis, RQA can be applied to non-stationary data, and provides a direct measure of the repetitiveness of the variability of the signals (percentage of determinism). The range of applications of RQA is large, but within biomechanical analyses it has previously been applied to measurements of center of pressure (Riley et al., 1999; Schmit et al., 2006; Hasson et al., 2008) and gait (Labini et al., 2012). This study is the first to apply RQA to analyze the consequences of LBP on spinal movement. Furthermore, it is the first study of LBP to separate the recorded signals into two different and functionally distinct components, and to demonstrate that the differences from healthy subjects reside in the structure of the accessory angular trajectory and not those directly related to the task execution when subjects were engaged in a highly controlled task.

When applying RQA a number of parameters must be set (number of embedded dimensions, time-lag for embedding, threshold applied to distance matrix; see Section 2 – data analysis). These parameters were set within the ranges used in previous studies in biomechanical data. Although none of these studies focused on spinal movements, the spectral bandwidth of these signals (e.g., CoP during stance) and the ones recorded in this study (Fig. 3) is similar, suggesting that similar RQA settings can be applied. In a preliminary data analysis we found that only the gain and offset of the average values of percentage of determinism was sensitive to variations of these settings, whereas the trends across the different angular sensors and the differences across the LBP and control group were consistently observed (results not shown), indicating that the choice of RQA parameters did not affect the overall conclusion.
LBP may involve an increase or a decrease in the magnitude of movement variability depending on the functional task and the type of measure applied. Only one study has previously addressed the structure of the mechanical variability (Lamoth et al., 2006). In that study, principal component analysis was applied to find that the variability of angular velocities in gait of LBP subjects were distributed across a higher number of components compared to controls. In the terminology of the current study, this implies a more random structure of the variability in LBP; the opposite of what was observed here. Differences in task (gait vs. lifting task) or LBP group characteristics (baseline pain intensity: 5.6 vs 1.8, baseline TSK: 44 vs 32) may explain this contradiction, but further investigations are required to determine this.

The results indicate the potential clinical utility of the device (Eponics SPINE) and the applied data processing methods. In spite of relatively low baseline pain rating levels and on average minimal functional impairment measured with the ODI, consistent differences were found between the LBP and control group. This may indicate that the structure of the variability of the accessory movement may be among the first mechanical and/or functional manifestations of LBP, and that changes seen in more commonly applied measures such as the magnitude of the variability and range of motion may occur when subjective pain intensity is more severe or persistent and functional impairment increases. Therefore, RQA could be a useful tool for detecting movement impairment in early stages of LBP and monitoring change with rehabilitation.

In conclusion, we recorded the angular dynamics of the spine during a repetitive lifting task in subjects suffering from LBP and healthy controls. Although the range and variability of the angular trajectories did not differ, using RQA, we found that the structure of the variability was more deterministic (less random) for the trajectories did not differ, using RQA, we found that the structure of the variability was more deterministic (less random) for the LBP group. The results have implications for the understanding of mechanical changes occurring in LBP.

Disclosure

Frank Petzke participated in one advisory board meeting of Eponics Medical GmbH (Potsdam, Germany) in 2011.

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