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The effect of muscle fatigue and low back pain on lumbar movement variability and complexity

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1. Introduction
Low back pain (LBP) is one of the most common musculoskeletal disorders in industrialized countries, with a high prevalence in occupations requiring heavy repetitive physical work for the lower back (Harcombe et al., 2014, Wang et al., 2015). Heavy repetitive physical work may provoke pain by accelerating lumbar spinal disease such as cumulative trauma disorders (Solomonow, 2012) typically caused by maintaining ergonomically poor postures such as working in a stooped position with a twisted back (Holtermann et al., 2013, Roffey et al., 2010, Seidler et al., 2011, Smedley et al., 1995, Yassi et al., 2013). Further, LBP has been associated with less structured variability of lumbar movement and more structured variability of accessory lumbar movement, which were measured by percentage determinism (%DET). These might indicate early functional manifestations of LBP (Bauer et al., 2015b, Dideriksen et al., 2014). Additionally less complex lumbar postural control, quantified by sample entropy (SaEn), is correlated to increased lumbar discomfort (Søndergaard et al., 2010). This association might be explained by affected trunk neuromuscular control in people suffering from LBP (Descarreaux et al., 2007, Lamoth et al., 2006, Silfies et al., 2009, Svendsen et al., 2013).

Fatigue is a physiological short-term outcome in repetitive movements and could be a precursor to musculoskeletal disorders such as LBP (Rempel et al., 1992). Adequate movement variability may lead to a slower development of fatigue by distributing load across adjacent tissues, and thus maintaining task performance (Farina et al., 2008, van Dieen et al., 2003). In the presence of fatigue, the neuromuscular system rapidly searches for a new movement solution so that task performance can be preserved. This is evidenced by increased movement variabilities after fatiguing, found both at the local site of fatigue as well as the whole body (Fuller et al., 2011). Motor variability in the non-fatigued state may predict the ability to perform prolonged work (Skurvydas et al., 2010). This indicates the neuromuscular system’s capability to produce sustained force during dynamic and repetitive tasks, by using variable muscle recruitment patterns. Recruitment variability, of both motor units and muscles, have a bearing on endurance during both sustained and intermittent isometric contractions of the corresponding muscles. This has been observed in trunk (van Dieen et al., 2003, van Dieen et al., 2009), and shoulder muscles (Falla et al., 2007, Farina et al., 2008, Palmerud et al., 1998). One unresolved question is whether these adaptations to fatigue are hampered by the presence of pain, as an impaired adaptation to fatigue might augment the development of musculoskeletal disorders. The purpose of this study was to therefore investigate if changes in movement variability and complexity after the onset of fatigue are influenced by LBP.
2. Methods
The degree of structure in the variability of lumbar movement and its complexity were assessed during a repetitive test before and immediately after an isometric endurance test to fatigue the lumbar musculature, in pain free people and people suffering from LBP. It was hypothesised that pain free people and people suffering from LBP differ in their response to fatigue. Anthropometric factors such as age, gender, or body mass index (BMI) which can influence lumbar kinematics (Consmuller et al., 2012) and the development of LBP (Heuch et al., 2015), were controlled for in the study design.

2.1 Participants
Fifty-nine participants with sub-acute or chronic LBP and 27 asymptomatic participants, aged between 18-65 years, were recruited from physiotherapy practices, the university campus and through newspaper advertisements. To be eligible participants with LBP had to fulfil the following inclusion criteria:

- a current episode of sub-acute or chronic non-specific LBP that persisted for four weeks or longer;
- a mean LBP intensity of ≥1 on the numeric rating scale (NRS) over the last four weeks;
- a moderate disability defined as an Oswestry-disability-index (ODI) >8%;
- a low level of psychosocial risk factors defined with less than four points on the psychosocial subscale of the STarT Back screening tool (Mannion et al., 2006).

Exclusion criteria were:

- specific LBP;
- vertigo or disturbance of the equilibrium;
- systemic diseases (diabetes, tumours);
- pain in other areas of the body (neck, head, thoracic spine, or arms);
- complaints, injury, or surgery of the legs (hips to feet) within the last six months;
- medication affecting postural control (e.g. anti-depressants);
- pregnancy.

In addition the asymptomatic participants were excluded if they had a LBP episode during the preceding three months. The study was conducted according to the declaration of Helsinki, and approved by the local ethics committee (KEK-ZH-2011-0522). Participants provided their written informed consent.
2.2 Experimental Procedures

Participants attended one measurement session and performed one “Repeated Flexion and Extension” test (Figure 2) (Bauer et al., 2015a), pre and post-fatiguing of the lumbar musculature. The test consisted of twenty cycles, of three seconds duration, starting in upright sitting. The duration of the complete test was 60 seconds. During each cycle the participants were asked to flex and extend their lumbar spine and hip as far as possible whilst adhering to the timed window. They were guided with a metronome set at 80bpm and were instructed to flex and extend their lumbar spine within two beats respectively. The participants were fixed at their thighs with two belts to prevent unintended movement of their pelvis and thighs. The test was performed one time pre and post-fatiguing, respectively. Prior to the pre-test the participants received standardized oral instructions by one of the examiners and visual instructions in a video. In case of poor initial performance these instructions were repeated up to three times and the test was demonstrated by one examiner. The participants performed the post-test immediately after completing an isometric endurance test (Biering-Sorensen, 1984) to fatigue the lumbar musculature.

The isometric endurance test is described elsewhere (Biering-Sorensen, 1984) and only briefly summarized here. The participants were lying in prone position on a physiotherapy bench that was tilted 45° downwards from the pelvis. The participants lower legs and thighs were fixated with two belts. They were instructed to lift their upper body from the bench and maintain it unsupported for as long as possible. When the participants could not maintain this any longer, or one investigator noticed that their upper body touched the bench, the test was ended and the post-test was performed immediately after. All participants received standardized verbal encouragement during the endurance test.

2.3 Movement Analysis

2.3.1 Sensor placement and data processing

Lumbar spine movement was measured by an inertial measurement unit (IMU) system, with IMUs placed over the level of the second sacral and first lumbar vertebra (Ernst et al., 2013) (Figure 1). The IMU system has been shown to provide concurrently valid estimates of spinal kinematics (Bauer et al., 2015a). The sensors of the IMU system (Valedo®Motion, Hocoma AG, Volketswil, Switzerland) include a tri-axial gyroscope, magnetometer, and accelerometer. Movement data were recorded with a sampling frequency of 200 Hz using customized software (Valedo®Research, Hocoma AG). The raw data from the IMUs were transformed into quaternions (Madgwick et al., 2010) and filtered using a second-order zero-phase low-pass Butterworth filter (6Hz cut-off frequency). Segmental kinematics were calculated using the tilt/twist formulation to prevent rotational singularities (Crawford et al., 1999) with sagittal plane defined by the global coordinate system. All outcome
variables were derived from the flexion/extension angle, where flexion is positive and extension is negative. An angle of zero degrees is defined as alignment of the IMUs. Angular velocity was calculated using the first derivative of the angular displacement data. A complete description of the data processing from raw data to tilt/twist angles is described elsewhere (Bauer et al., 2015a).

2.3.2 Outcomes
Percentage determinism (%DET) and sample entropy (SaEn) were calculated from angular displacement and velocity data (Figure 3). %DET and SaEn describe different aspects of a time series signal: %DET indicates the predictability of a signal by providing an indication of the structure in variability. Lower %DET implies a lower degree of structure in the signals variability (Webber and Ziblut, 1994). SaEn is a measure of complexity. Lower SaEn indicates that a signal is less complex (Richman and Mooreman, 2000). As such the future state of the time-series is less complex and more predictable. To calculate both parameters %DET and SaEn, movement data were projected into a phase space by taking time-delayed samples from the movement data. The time-delayed samples represent movement patterns which can be visualized as points in the phase-space plot. The vectors consisting of the time-delayed samples are called embedding vectors.

Recurrence quantification was used to calculate %DET. In recurrence quantification analysis, similar movement patterns are located close to each other, and form a cluster of recurrent points ($R_{ij}$) (Webber and Ziblut, 1994). The similarity of movement patterns is quantified by calculating the Euclidean distances between the embedding vectors. In this study, the phase-space reconstruction was undertaken separately for angular displacement and velocity data by using the set of parameters specified in Table 1. All $R_{ij}$s were subsequently transferred into a $N \times N$-sized recurrence plot (RP) (Figure 4) with $N$ being the number of points in the RP. %DET is the amount of $R_{ij}$s that form diagonal lines (i.e. are sequential to each other in time) of a prespecified minimal length ($l_{min}$) given in Table 1. The %DET is expressed as:

$$%DET = \frac{\sum_{l=l_{min}}^{l_{max}} l \times P(l)}{N \times N} \times 10^2$$

with $l$ being the length of the diagonal lines, $l_{max}$ the maximal possible length of the diagonal lines, and $P(l)$ being the number of diagonal lines of length $l$.

To calculate SaEn, the similarity of movement patterns was quantified by calculating the distances between the embedding vectors as the maximum difference of their corresponding scalar components. The length of created embedding vectors was $m$ and $m+1$. SaEn was calculated as:

$$SaEn = - \ln \left( \frac{\phi^{m+1}(r)}{\phi^{m}(r)} \right)$$
with $\Phi$ being the probability that two embedding vectors are similar in comparison to previously defined tolerance $r$ (Richman and Mooreman, 2000). All data processing and calculations were done using Matlab 2012b* (Mathworks, USA), with %DET code from University of Potsdam, Germany (Marwan and Kurths, 2002) and SaEn code from Nanyang Technological University, Singapore (Lee, 2012).

2.4 Statistical Analysis

For each outcome a linear mixed model for observation $Y_{ijk}(k_{th}$ participant in the $i_{th}$ group at time $j$) was modelled with

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha \beta)_{ij} + U_{k(i)} + \beta_{covariates} + \epsilon_{ijk}$$

with $\alpha_i$ as the $i_{th}$ group (LBP/painfree) effect, $\beta_j$ as the $j_{th}$ fatigue effect, $(\alpha \beta)_{ij}$ as the $ij_{th}$ group-fatigue effect, $U_{k(i)}$ as the effect of subject $k$ nested in group $i$, $\beta_{covariates}$ as the effect of age, gender and BMI, and $\epsilon_{ijk}$ as measurement error. We assume that $U_{ik} \sim N(0, \nu^2)$ with $\nu^2$ as the between-subject variance and $\epsilon_{ijk} \sim N(0, \tau^2)$ with $\tau^2$ as the within-subject variance. Bayesian estimation of the model parameters was performed by using uninformative priors on the model parameters. We used Monte-Carlo-Markov-Chain (MCMC) algorithms with Gibbs sampling (Plummer, 2003) to sample from the posterior distributions. We created point estimates of group-fatigue effects and 95% Highest Posterior Density intervals (95%HPDI) for the parameters in an MCMC sample. The repeatability of %DET and SaEn is presented in supplementary file 1. A group-fatigue effect would indicate that one group responds differently to fatigue compared to the other. The probability that the magnitude of this effect is within the borders of the 95%HPDI is 0.95. The HPDI is thus comparable to the confidence interval in frequentist statistics. Statistical analysis was conducted using R (R Foundation for statistical computing, Austria).

3. Results

The descriptive characteristics, group-fatigue effects and corresponding 95%HPDI are presented in Table 2. Pain free participants showed more complex and less predictable lumbar movement, with a lower degree of structure in its variability while participants suffering from LBP did not. This effect was only observed, after an isometric endurance test, in lumbar angular velocity, but not in angular displacement. %DET and SaEn of angular displacement did not show a group-fatigue effect, indicated by the 95%HPDI crossing 0. Angular velocity %DET decreased and SaEn increased more distinctively in the painfree group, indicating a group-fatigue effect, with the 95%HPDI not crossing 0. The group-fatigue effects on %DET and SaEn are illustrated in Figure 5. Additionally, angular velocity %DET
decreased -0.2, while SaEn increased 0.001 per year of age. Gender and BMI had no effect on %DET and SaEn.

4. Discussion
This study revealed that pain free participants displayed more complex and less predictable lumbar movement with a lower degree of structure in its variability following an isometric endurance test to fatigue lumbar musculature while participants suffering from LBP did not. This effect was only observed in lumbar angular velocity during a repetitive movement test, but not in lumbar angular displacement.

These findings indicate that the presence of LBP influences a person’s response to fatigue. Pain free persons might adapt to fatigue by showing more complex and less predictable lumbar movement with a lower degree of structure in its variability which is theorized as a strategy to reduce load on fatiguing tissues, while preserving task performance. Evidence suggesting that changes in movement variability may help in preserving performance during a fatiguing task has been reported in repetitive throwing (Forestier et al., 1998, Huffenus et al., 2006), repetitive reaching (Fuller et al., 2011), cross-country skiing (Cignetti et al., 2009), hammering tasks (Cote et al., 2008, Cote et al., 2005), and repeated elbow flexion/extension for tracking a target (Selen et al., 2007). On the other hand, people suffering from LBP may be unable to adapt their movement strategy by making use of the musculoskeletal systems redundancy, thus accumulating load on fatiguing tissues. This could be explained by pain induced changes in muscle and motor unit recruitment patterns that have been observed under experimental pain conditions (Falla et al., 2009, Farina et al., 2012, Muceli et al., 2014, Yavuz et al., 2015).

On the contrary the present findings might indicate that pain free participants were able to control their lumbar movement before the onset of fatigue, but lost control of lumbar movement after the onset of fatigue, thereupon resembling participants suffering from LBP. This is indicated by the less complex and more predictable lumbar movement with a higher degree of structure in its variability that pain free participants showed during pretest. This interpretation would imply that more structured movement variability might actually be beneficial and represent better movement control during repetitive tasks. This hypothesis is supported by findings that less structured lumbar movement variability is associated with increased LBP intensity (Bauer et al., 2015b). Furthermore it might indicate an inability of the lumbar para-spinal muscles to stabilize the lumbar spine in the neutral zone. This hypothesis should be addressed in a future study on lumbar muscle recruitment patterns.
The optimal, or healthy, complexity and degree of structure in variability needed to prevent lumbar musculoskeletal disorders is unknown. The presence of variability in movement patterns may represent the underlying physiological capability to make flexible adaptations to everyday stressors placed on the neuromuscular system (Lipsitz, 2002, Lipsitz et al., 1992). In contrast, the presence of ergonomically poor movement patterns might increase the measured movement variability, thus elevating tissue loading. Therefore, a non-linear or U-shaped relationship between structure, complexity and disease is hypothesised (Stergiou et al., 2011), and reported by previous studies: More structured variability of lumbar movement (Bauer et al., 2015b) but less structured variability of accessory lumbar movement (Dideriksen et al., 2014) were associated with LBP, which might indicate early functional manifestations of LBP. Larger and smaller sizes of arm and trunk movement variability were found during simulated low-load repetitive work in people suffering from acute and sub-acute or chronic pain respectively (Madeleine, 2010).

A limitation of the present study is that the true size of the effect of fatigue on the complexity of lumbar movement and the degree of structure in its variability remains unknown since this study did not include a measure of lumbar muscular fatigue. This indicates the need to record EMG data to supplement kinematic analyses and analyse changes in %DET of EMG data pre and post fatigue. Increases in %DET have been reported in the presence of fatigue; which reflects higher periodicity (Felici et al., 2001). The inclusion of a measure of lumbar strength could have helped to quantify if both groups were equally influenced by the protocol. Future studies might consider additional lateral flexion, and rotation angles. They were not analysed due to the IMU systems limited concurrent validity when measuring lateral flexion or rotation movements of small magnitude during large flexion extension movements (Bauer et al., 2015a). Furthermore, the current study design does not enable to say if the difference in response to fatigue is a cause or a result of LBP. Still, this study demonstrated that changes in lumbar movement velocity after an isometric endurance test are influenced by the presence of LBP.

This study shows that painfree people differ in their kinematic response to fatigue compared to people suffering from LBP. Future studies should combine measures of lumbar kinematics with measures of cortical representation and muscle recruitment patterns to improve our understanding of the underlying mechanisms. Further, those measures should be combined with work performance measures, to evaluate whether the observed changes following fatigue preserve an individual’s task performance. Eventually, longitudinal prospective studies should investigate the development of LBP and corresponding changes in complexity of lumbar movement and structure of its variability, to assess whether these changes are a cause or consequence of LBP.
Conclusions
The effect of fatigue on the complexity of lumbar movement and the degree of structure in its variability was analysed in pain free participants and participants suffering from LBP, and controlled for the effect of age, gender and BMI. A group-fatigue effect on lumbar movement velocity was found, meaning that pain free people show more complex and less predictable lumbar movement velocity with a lower degree of structure in its variability, while people suffering from LBP do not. These findings indicate that the presence of LBP influences a participant’s response to an isometric endurance test.

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Fig 1.
Experimental setup: IMUs were placed on the level of sacrum (S2) and L1 (L1).
Fig 2. Repeated Flexion and Extension Test
Fig 3. Angular Displacement and Velocity Data Pre and Post Fatigue

The left column shows angular displacement and velocity of a pain free participant, the right column a participant with low back pain. Determinism decreases, while sample entropy increases in the pain free participant.
Figure 4. Recurrence Plots of Angular Displacement and Velocity Data Pre and Post Fatigue
The left column shows angular displacement and velocity of a painfree participant in, the right column a participant with low back pain. Determinism decreases, post fatigue, in the pain free participant.
Fig 5. Interaction plots for the primary outcomes pre and post fatigue
Abbreviations: % DET – percentage determinism; LBP – low back pain; SaEn – Sample Entropy
Table 1 Input parameters used in recurrence quantification analysis and sample entropy calculation

<table>
<thead>
<tr>
<th></th>
<th>Recurrence Quantification Analysis</th>
<th>Sample Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delay</td>
<td>Embedding Dimension</td>
</tr>
<tr>
<td>Angular Displacement</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>Angular Velocity</td>
<td>21</td>
<td>2</td>
</tr>
</tbody>
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Imin - minimal length of diagonal line; SD – standard deviation

The delays were estimated using mutual information analysis. The first minimum of mutual information was defined as the optimal delay. The embedding dimensions were estimated by calculating the correlation dimension with different embedding dimensions. The optimal value of the embedding dimension was chosen as the starting point where the correlation dimension did not increase significantly although increasing the embedding dimension. The tolerance for determining a recurrent point in the reconstructed state-space was calculated from the standard deviation of the phase space trajectory. The optimal minimal length of diagonal line was chosen after visual inspection of the recurrence plots.
Table 2 Descriptive Statistics and Group-Fatigue Effect

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Gender</th>
<th>Age (years)</th>
<th>BMI (kg/m²)</th>
<th>Time to Fatigue (seconds)</th>
<th>Fatigue</th>
<th>RoM (%)</th>
<th>Angular Displacement %DET</th>
<th>SaEn</th>
<th>Angular Velocity %DET</th>
<th>SaEn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>Painfree</td>
<td>27</td>
<td>12/15</td>
<td>39.6 (±11.6)</td>
<td>22.7 (±2.8)</td>
<td>161.8 (±63.3)</td>
<td>Pre</td>
<td>60.0 (±14.9)</td>
<td>62.8 (±2.9)</td>
<td>2.4 (±0.3)</td>
<td>36.2 (±8.8)</td>
</tr>
<tr>
<td>Post</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Post</td>
<td>61.7 (±21.8)</td>
<td>63.3 (±2.9)</td>
<td>2.5 (±0.5)</td>
<td>32.1 (±9.3)</td>
<td>11.2 (±3.6)</td>
</tr>
<tr>
<td>Pre</td>
<td>LBP</td>
<td>59</td>
<td>30/29</td>
<td>39.1 (±12.8)</td>
<td>24.0 (±3.6)</td>
<td>153.8 (±56.8)</td>
<td>Pre</td>
<td>59.5 (±19.1)</td>
<td>64.6 (±3.9)</td>
<td>2.4 (±0.4)</td>
<td>34.9 (±8.1)</td>
</tr>
<tr>
<td>Post</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Post</td>
<td>61.6 (±22.4)</td>
<td>64.4 (±4.2)</td>
<td>2.5 (±0.6)</td>
<td>34.4 (±9.8)</td>
<td>11.8 (±3.7)</td>
</tr>
</tbody>
</table>

Statistics

<table>
<thead>
<tr>
<th>Group-fatigue effect</th>
<th>95% HPDI</th>
<th>95% HPDI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.6</td>
<td>-0.1</td>
</tr>
<tr>
<td>95% HPDI</td>
<td>-2.4 – 1.0</td>
<td>-0.4 – 0.2</td>
</tr>
</tbody>
</table>

95% HPDI - 95% highest posterior density interval; BMI – body mass index; %DET – % of determinism; LBP – low back pain; NRS numeric pain rating scale; RoM – range of motion lumbar spine; SaEn – sample entropy.

Results are provided as mean (±standard deviation); Bold numbers indicate the 95% HDPI not crossing 0. SaEn values are expressed as *10².