Analysis of Standing Balance on Sloped Surfaces in Individuals with Lumbar Disc Herniation*

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Abstract—The change of balance control mechanism caused by lumbar disc herniation (LDH) has not been well understood. The aim of the study was to investigate the effects of LDH on the dynamical coordinations of center of pressure (COP) during standing on sloped surfaces. Eight LDH patients and 8 gender- and age-matched healthy subjects were recruited to participate in the experiment. Three surface conditions (declining, level and inclining) were set up. Limb load asymmetry (LLA) and individual leg COP (COPmore-affected and COPless-affected) were calculated from the foot pressure distributions which recorded during quiet standing by a force plate. Cross recurrence quantification analysis (CRQA) was applied to assess the coordination of COP trajectories. Linear cross-correlation was applied to measure the correlation between CRQA parameters and COP area. LDH patients showed higher LLA and more deterministic structure of less-affected leg, especially on sloped surfaces, but there is not much difference in more-affected leg. CRQA parameters showed positive correlation with COP area on sloped surfaces. This study reveals that the LDH patients alter the postural control mechanism by magnifying the inter-limb asymmetry and reinforcing feedforward mechanism. The sloped surfaces magnified the changes of more deterministic and rigid patterns in less-affected side in the LDH. This study may provide a new strategy for clinical diagnosis and evaluation of LDH.

I. INTRODUCTION

Lumbar disc herniation (LDH) is a disturbing disease usually caused by degeneration or trauma that the nucleus pulposus breaks through the anulus fibrosus of an intervertebral disc. The clinical syndromes of LDH include lower back and leg pain, sciatica, muscle spasm or cramping, and leg weakness or loss of leg function. Exams and tests such as physical exam, nerve electrophysiological test, and different balance control mechanism from that of healthy subjects. We also hypothesized that CRQA parameters would be associated with traditional measures of postural steadiness.

REFERENCES

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Their leg pain was greater than low back pain, one leg was more affected and spine was without scoliosis. All participants who had a history of cardiovascular, cerebrovascular, vestibular diseases, musculoskeletal injuries on their lower-extremity were excluded from our study. The characteristics of LDH subjects are shown in Table I. The experimental procedures involving human subjects described in this paper were approved by the Institutional Review Board of Shandong University. All subjects signed the informed content prior to participating in the experiment.

### TABLE I. CHARACTERISTICS OF SUBJECTS WITH LDH

<table>
<thead>
<tr>
<th>Number</th>
<th>Gender</th>
<th>Age (y)</th>
<th>Level of LDH</th>
<th>More Affected leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>56</td>
<td>L4-L5, L5-S1</td>
<td>Left</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>50</td>
<td>L4-L5</td>
<td>Left</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>37</td>
<td>L4-L5, L5-S1</td>
<td>Left</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>35</td>
<td>L5-S1</td>
<td>Left</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>61</td>
<td>L3-L4</td>
<td>Right</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>69</td>
<td>L5-S1</td>
<td>Right</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>61</td>
<td>L3-L4, L4-L5</td>
<td>Left</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>45</td>
<td>L5-S1</td>
<td>Right</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>51.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>12.15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* L = Lumbar, S = Sacral.

### B. Experimental set-up

The data of foot pressure distributions was obtained by a force plate FDM-S (Zebris Medical GmbH, Germany, Isny) at a sampling rate of 60 Hz. The COP time series and follow-up data analysis were processed in MATLAB R2017b (The Mathworks, Natick, MA, USA).

### C. Experimental procedures

Three surface conditions were tested under a randomized sequence in this study, including declining (-5°), level and inclining (5°) surfaces. The schematic diagram of the experiment set-up is depicted in Fig.1. Subjects were conducted to stand barefoot quietly on the force plate with feet side by side and hands hanging loosely by sides under the conditions of visual feedback for 15 s. Taking the physical condition of LDH patients into account, each surface condition was tested only once. During the test interval, subjects sat still.

### D. Data analysis

The body weight has been confirmed that has an unequal distribution in certain degree. In our study, we defined the limb load asymmetry (LLA) as the ratio of the body weight on the less-affected side to that on the more-affected side [6] to explore whether patients with LDH would reduce the weight on the more-affected side to relieve the pain. The more-affected leg and less-affected leg of healthy subjects were determined according to the LDH patients they matched [7]. If one patient’s more-affected leg is the left leg, then the more-affected leg is the left leg and less-affected leg is the right leg for the paired healthy subject, and vice versa [7].

The individual leg COP (COP\textsubscript{more-affected} and COP\textsubscript{less-affected}) can be calculated from the data of foot pressure distributions according to the concept of the center of parallel forces. The nonlinear interrelation between the COP trajectories in AP and ML directions was quantified by CRQA. Cross recurrence rate (Cross-RR), cross determinism (Cross-DET) and cross entropy (Cross-ENT) are three commonly used parameters provided by CRQA [4]. The time delay and embedding dimension were determined by mutual information and false nearest neighbors, respectively [4]. The value of radius which kept the proportion of recurrence points below 10% was chosen. Finally, a time delay 10 samples, an embedding dimension 4 and radius 30% of the maxim distance between data points in the reconstructed space were used to reconstruct the phase space. The Area of COP is the area of the 95% bivariate confidence ellipse, which is expected to enclose approximately 95% of the points on the COP path [8]. Window with the size of 500 samples and with an overlap of 100 samples were used to calculate the indicators above. Fig 2 exhibits the CRPs of COP\textsubscript{more-affected} COP\textsubscript{less-affected} of an LDH patient and paired healthy subject.

All statistical analysis were performed using SPSS 23.0 (SPSS Inc., Chicago, IL). For CRQA parameters, data were compared between three groups: the more-affected and less-affected legs of LDH patients, and the controls (only the more-affected leg was selected) [7]. An independent t-test was carried out to examine the differences between the LDH and control groups. A paired t-test was carried out to examine the difference between the sloped and level surfaces, more-affected and less-affected sides of the LDH patients. Linear cross-correlation was applied to measure the correlation between CRQA parameters and COP area. A p-value of less than 0.05 was considered as statistically significant.
III. RESULTS

Time series of the LLA is depicted in Fig 3. Different to LLA of healthy subjects which was close to 1, the LLA of LDH patients was much larger than 1 and with greater variability.

![Figure 3. Time series of the LLA. (A) declining surface; (B) level surface; (C) inclining surface.](image)

Results of CRQA for the individual leg COP are shown in Fig 4. Group difference between less-affected side of LDH group and control group were only observed in Cross-RR of 5° slope - inclining surface and Cross-DET of -5° slope - declining surface (Fig 4, p<0.05). The Cross-RR of more-affected side of LDH group and Cross-DET of control group on declining surface were significantly lower than the parameters corresponding to the level (Fig 4, p<0.05). In addition, we can find that the less-affected side of LDH had greatest values than these of other two groups.

![Figure 4. Statistical analysis of CRQA parameters for individual leg COP.](image)

IV. DISCUSSION

The study aimed to investigate the effects of LDH on the dynamical coordination of COP during standing on the sloped surfaces using CRQA. LLA, dynamical coordinations of individual leg were evaluated. Cross-RR, Cross-DET and Cross-ENT of CRQA were chosen to be indicators of balance control capacity. The increased Cross-RR, Cross-DET and Cross-ENT relates to a higher regularity, a more deterministic structure and an augmented complexity of the deterministic structure in the dynamical coupling of COP, respectively. Linear cross-correlation was used to identify the association between CRQA parameters and COP area.

The results of LLA indicated an increase of asymmetric distribution of body weight in LDH. The patients would like to make the less-affected side to bear greater proportion of body weight to reduce the pain of more-affected side, resulting in stronger coupling of COP_less-affected [9].

The CRQA parameters of COP_less-affected in LDH group is higher, revealing that the temporal structure of COP in
less-affected side is more regularity and deterministic. More restricted posture limits the degree of adaptability and cannot respond to external perturbations well [9]. In order to improving overall performance of balance control, the more-affected leg, bearing smaller proportion of body weight, should compensate for the flexibility. However, we didn’t find any difference between the more-affected side of LDH group and control group in CRQA parameters. Despite adopting weight transfer strategy, the overall performance of balance control in LDH group still hasn’t improved. In addition to the limitation of pain of more-affected leg, the situation can also been explained from the reduction sensations caused by LDH. Healthy people need to adjust neuromuscular activations according to the feedback of real-time sensory information to keep balance. The dysfunction of sensory system force the LDH patients to rely on more feedforward mechanism which is preprogramming motor command, rendering more deterministic structures [10].

The positive correlations between CRQA parameters and COP area once again reveal effectiveness of CRQA in physiological sense. High CRQA parameters closely link with greater COP area, which represents poor balance control performance, but they help us to understand balance change from other deeper aspects - stronger coupling and more rigid patterns in dynamical aspect.

Group difference, correlation between CRQA parameters and COP area occurred during standing on sloped surfaces. Sloped surfaces not only make subjects rely on more sensory information related to forces and load, but also force them to change the muscle activation and joint stiffness [1, 2]. Such higher requirements of control system may result in that LDH patients, who have dysfunction of sensory and motor system, cannot meet the requirements well and adopt more feedforward mechanism and stiffness strategy.

V. CONCLUSIONS

The less-affected side of LDH patient bore more body weight and had more deterministic structure of COP coordination, the more-affected side compensated for the flexibility ineffectively, resulting in poor balance control performance. The sloped surfaces magnified the rigid balance control. This research sheds light on the effects of LDH on the standing balance control mechanism and may provide a new idea for the diagnosis and evaluation of LDH.

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REFERENCES