

Changes in Trunk Variability and Stability of Gait in Patients with Chronic Low Back Pain: Impact of Laboratory Versus Daily-living Environments

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Abstract

This study investigated the impact of environment and pathology in trunk variability and stability of gait among individuals with CLBP. CLBP patients (n = 20) and healthy controls (HC) with no LBP history (n = 20) attached an accelerometer to the low back and performed gait in laboratory and daily-living settings. We calculated stride-to-stride standard deviation (SD) and multiscale sample entropy (MSE) as “gait variability” and maximum Lyapunov exponents (LyE) as “gait stability” in both the anterior-posterior (AP) and medial-lateral (ML) directions. In repeated-measures ANOVA, SD was affected by environment in the AP direction and by group and environment in the ML direction. MSE showed no effect in the AP direction and both effects in the ML direction. LyE showed both effects in the AP direction, but none in the ML direction. These change of trunk motor control by LBP have a relation to pain intensity, fear of movement and/or RMDQ in the daily-living but not laboratory settings. Evaluation of adaptation to environment in CLBP will enhance our understanding of changes in sensory-motor control and contribute to optimal management of such patients.

1. Introduction

Individuals with chronic low back pain (CLBP) are known to have characteristic spatiotemporal gait parameters including step length, cadence and stride-to-stride variability¹⁻⁵. In addition, they frequently present with impaired lumbar movements such as a decline movement velocity and a reduced range of movement⁶. In general, motor control is affected among individuals with LBP in the way that Hodges propose that changes occur at multiple levels of the motors system. Pain and/or pain-related fear reportedly alters motor variability and trunk stabilization as motor system adaptations in individuals with LBP⁷. However, this effect has not been clarified in relation to gait. Gait variability is a reflection of the multiple degrees of freedom of the sensory-motor system⁸. Both standard deviation (SD), which is one of the classical linear estimates, and multiscale sample entropy (MSE), which is based on the quantification of complexity on multiple scales of time series, have been used to evaluate gait variability⁹⁻¹¹. On the other hand, gait stability is considered the ability of the individual’s sensory-motor control system to maintain gait in the situation of omnipresent disturbances, and is often evaluated by the maximum Lyapunov exponent (LyE), which is a nonlinear measure of local dynamic stability¹²⁻¹⁴. Uncovering the variability and stability of gait pattern could provide more insight into the behavioral changes in individuals with LBP.

Previous studies employing a single wearable sensor to evaluate gait reported that variability and/or stability of gait are affected more in the daily-living than the laboratory or clinical setting¹⁵⁻¹⁷. In particular, healthy young adults routinely vary their motor patterns to maintain stability in unstructured environments¹⁷. Measuring gait in daily living reflects habitual gait performance^{18,19}; thus, recording daily-living gait has the potential benefits of detecting gait impairment in unsupervised and uncontrolled conditions^{20,21}. Moreover, gait in unstructured daily living is more difficult to predict and hence prone to disturbance than that in structured clinical settings. Compared to healthy adults, individuals with CLBP

may show increased gait variability and decreased gait stability in daily living secondary to changes in trunk motor control based on pain and/or pain-related fear.

Therefore, this study aimed to use measures of SD, MSE and LyE to explore the impact of environment and pathology by analysing differences of trunk variability and stability of gait between individuals with LBP and healthy controls in both laboratory and daily-living environments. In addition, we investigated the relationship between trunk motor controls of gait and pain and/or fear. As our hypotheses, we posited that between-group and/or between-environments differences would be more apparent in CLBP, and that trunk motor controls of gait would show a relationship to symptoms of CLBP.

2. Subjects And Methods

2.1. Subjects and assessment

We recruited twenty healthy participants (mean age 56.75 ± 9.43 years) from our laboratory's geographic region using flyers, and twenty chronic low back pain patients (mean age 54.05 ± 10.76 years) from an orthopedic clinic. The inclusion criteria for the experimental group were as follows: a low back pain (LBP) duration of > 3 months; a score of ≥ 1 on an 11-point numeric rating scale (NRS, 0–10) for pain intensity; sufficient walking ability to travel to our laboratory without assistance. The exclusion criteria were as follows: previous spinal surgery (fusion, instrumentation, or discectomy), lumbar infiltration in the last 6 months, serious spinal pathology (cancer, inflammatory arthropathy, or acute vertebral fracture), a diagnosis of neurological disease, and a stage of ≥ 2 on a functional assessment staging test of Alzheimer's disease. The study protocol conformed to the Declaration of Helsinki. Before participating, each participant provided written informed consent. This study was approved by the Ethics Committee of Kio University Health Science Graduate School (approval no. H30-20).

2.2. Data collection in the laboratory and daily-living

In the laboratory, each CLBP patient was instructed to fill out 3 questionnaires about LBP. Average pain intensity over time was assessed on an 11-point numerical rating scale (NRS: 0 = no pain and 10 = highest possible degree of pain). Kinesiophobia was assessed using the 11-item version of the Tampa Scale for Kinesiophobia (TSK-11:11 = no fear of movement and 44 = highest fear of movement)²², and physical disability caused by LBP was assessed on Roland–Morris Disability Questionnaire (RMDQ: 0 = no physical disability and 24 = worse physical function)²³.

Next, each participant was asked to wear a single wearable tri-axial accelerometer (Axivity AX3, York, UK) on the fifth lumbar vertebra (L5). The device was programmed to capture data at 100 Hz and at a range of ± 8 g²⁴. In the laboratory environment, participants walked over 60 seconds at their preferred speed around an indoor track (30 m/loop). After undergoing the clinical assessment, participants were asked to wear a single wearable sensor for three days in a daily living environment; i.e., to continue their daily activities as usual²⁵.

2.3. Data processing and analysis

Description of Acceleration-Derived Variables

All data analysis relating to the raw acceleration signals was performed using custom-made MATLAB R2019b (MathWorks BV, USA). The algorithm and data segmentation techniques applied to the accelerometer data have already been described in full ^{24,26}. In brief, the vertical acceleration underwent continuous wavelet transformation to estimate the initial contact and final contact in the gait cycle ²⁶. To ensure that steady-state gait was analyzed, the initial and final three steps were removed from the data captured over 60 seconds. In a daily living environment, A mean of 15.75 walking epochs (range: 6 to 32) with duration over 60 seconds were identified for each of the healthy participants. Similarly, a mean of 15.15 walking epochs (range: 5 to 26) with duration over 60 seconds were identified for each of the CLBP patients. Prior to the calculation of additional variables, the acceleration signals were realigned to the earth's gravitational constant, and a low-pass Butterworth filter with a cut-off frequency of 20 Hz was applied ^{27,28}. The following variables were calculated using the accelerations of anterior-posterior (AP) and medial-lateral (ML) directions since directional control of movement is performed independently ²⁹.

Trunk variability of gait

Standard Deviation (SD)

To compute stride-to-stride variability of gait, trunk acceleration during each stride was time-normalized (0–100%). At each of the 101 normalized time points, the SDs of AP and ML trunk acceleration were calculated. Next, the average SD of these 101 SDs was calculated ⁹.

Multiscale sample entropy

Multiscale entropy (MSE) is a nonlinear analysis to quantify the complexity of biological signals based on the dynamical system theory that the dynamics of motor behavior results from interaction between the nervous system, body and the environment in the performance of a particular task on multiple spatio-temporal scales ^{10,11}. This measure is more sensitive than linear variability and can serve for investigating complexity in motor control ³⁰. This index aims at quantifying the predictability of patterns, a time series containing many repetitive patterns (i.e., one that is more predictable) would have a relatively small MSE, whereas a less predictable process would have a higher MSE and smaller regularity ¹⁰. A range of τ -values (from 1 to 6) were used to analyse entropy at different time scales, while preserving the characteristics of the original time series. The length of sequences to be compared, m , was fixed at 2 and the tolerance for accepting matches, r , at 0.2 ^{31,32}.

Trunk stability of gait

Maximum Lyapunov exponents

Maximum Lyapunov exponent λ (LyE) is a popular method to quantify dynamical stability of gait and the ability of the motor system to attenuate small perturbations, defined as the divergence of trajectories in state space¹². LyE thus measures the exponential rate of divergence of trajectories of state space constructed from kinematic data acquired from gait³³. An inability of the motor system to diminish perturbations results in a higher divergence of the trajectories of state space and thus greater LyE values. Hence, the higher the LyE value, the lower the stability of the individual's gait^{14,34}. LyE values were calculated using the method defined by M.T. Rosenstein et al.³⁵. The state space reconstruction was composed of delay-embedded state spaces ($q(t)$, $q(t + \tau)$, $q(t + 2\tau)$...) of unfiltered ML and AP acceleration components. Time delays τ were calculated from the first minimum of the average mutual information function. An embedding dimension of $dE = 5$ was used for all data sets, as determined from a global false-nearest-neighbour analysis. LyE was calculated as the slope of the logarithm of the average divergence across the span of 0–0.5 strides as shown in Fig. 1.

Statistical analyses

We used the software program R (version 3.4.1) for all statistical analyses. We compared the age and gender distribution between the HC and CLBP groups by using the t-test and chi-squared test, respectively. For trunk motor controls of gait, a $2 \cdot 2$ [Environment (Lab/daily living) · Group (HC/CLBP)] repeated measures analysis of variance (RM-ANOVA) was conducted in the ML and AP directions. Partial eta square (η_p^2) values were calculated to identify effect sizes. Independent and dependent t tests were used for post hoc analysis when significant group by condition interactions were identified. Independent t tests were used to compare demographics between groups, and d values were calculated to indicate effect sizes. In addition, the associations between trunk motor controls of gait and symptoms of CLBP were evaluated using Pearson product-moment correlation coefficients. Analysis was corrected for multiple comparisons using Holm corrections³⁶.

3. Results

Table 1 presents the demographic characteristics of the HC and CLBP groups and the symptoms of the CLBP group. No significant differences emerged between the sample characteristics of HC and those of CLBP (age $p > 0.05$ on independent samples t-test; gender $p > 0.05$ on chi-squared test).

Figure 2 presents mean values and SDs for trunk variability and stability of gait in the HC and CLBP groups, and Table 2 presents RM-ANOVA for trunk variability and stability of gait in the CLBP group. In the AP direction, the RM-ANOVA of the SD revealed significant main effects for Group but not for

Environment. LyE showed significant main effects for Environment and Group. The RM-ANOVA of MSE revealed no significant main effects for Environment or Group. In the ML direction, the RM-ANOVA of the SD revealed significant main effects for Group and Environment, but the RM-ANOVA of LyE revealed no significant main effects for Group and Environment. An MSE of $\tau = 1$ showed significant main effects for Group but not for Environment. An MSE of $\tau \geq 2$ showed significant main effects for Environment and Group, and revealed that the interaction of Environment \cdot Group was significant. The post hoc analyses were performed by MSE at $\tau \geq 2$ for ML and revealed that the occurrence of MSE at $\tau \geq 2$ in daily living was significantly higher than that in the lab for the CLBP group. In addition, MSE at $\tau \geq 4$ in CLBP was significantly higher than that of the controls in the lab setting, while MSE at $\tau \geq 2$ in CLBP was significantly higher than that of the controls in the daily-living setting.

The associations between trunk motor controls of gait and symptoms of CLBP are presented in Fig. 3. In the lab, the only significant correlation was between SD of the ML direction and TSK-11. On the other hand, in daily living, the LyE of the AP direction was associated with both TSK-11 and RMDQ, and the SD of the ML direction was associated with TSK-11. MSE at $\tau \geq 5$ in the ML direction was also associated with NRS and TSK-11.

Discussion

In this study, we used a single wearable sensor, placed on the lower back, to assess trunk variability and stability of gait in individuals with chronic low back pain (CLBP) and healthy controls (HC) in laboratory and daily-living environments. We hypothesized that individuals with CLBP have increased gait variability and decreased gait stability in daily living compared to HC.

Our results were as follows: (1) the standard deviation (SD) of trunk acceleration (i.e. trunk variability) in the CLBP group was high regardless of environment in the Anterior-Posterior (AP) direction and high but affected by environment in the Medial-Lateral (ML) direction. (2) Multiscale sample entropy (MSE) (i.e. complexity) was not affected by CLBP status or by environment in the AP direction but was high in the CLBP group and affected by environment in the ML direction. In addition, the MSE at $\tau \geq 2$ was higher in the CLBP group in the daily-living setting. (3) The maximum Lyapunov Exponent (LyE) (i.e. trunk stability) was high in CLBP and affected by the environment in the AP direction, but was not affected by CLBP status or environment in the ML direction. (4) These changes of trunk motor control by CLBP have a relation to pain intensity and/or fear of movement and/or ADL deficits in the daily-living but not lab setting. Overall, our results supported our hypothesis that individuals with CLBP would show increased trunk variability and decreased stability of gait, but the AP and ML directions showed differences in these trends of trunk variability and stability of gait.

Trunk variability of gait was increased in the daily-living setting in the CLBP group. Gait in the unstructured environment of daily living may be more difficult to predict and prone to perturbations than in structured clinical settings, because the unstructured environment reinforces the need to adapt movements with a high degree of freedom (DOF). On the other hand, gait in daily living can be interpreted

as a cognitively dual task, and daily activities often incur a heavier cognitive load. It was previously reported that those with CLBP showed increased trunk variability in dual-task walking by loss of automatism of the sensory-motor control system due to chronic pain⁴. In the perspective of spinal structure, the lumbar spine has the largest DOF number and therefore greater problems with controlling position, especially with high loads and in unpredictable settings³⁷. The loose control (i.e. increased trunk variability) can cause LBP, as large displacements after trunk perturbations are associated with LBP and failures of muscular control over the spine result in large tissue strains^{37–39}.

The increased complexity of gait in CLBP that we showed in this study is consistent with the results of previous studies^{40–42}. It also has been reported that gait complexity increases in lumbar spinal stenosis patients and is directly related to the intensity of low back pain⁴³. Change in the neuromuscular control and/or pain may compel participants to compensate by adjusting their gait pattern. Also, the effect of environment or group increases with time delay τ , in agreement with the previous research^{44,45}. In particular, a τ higher than 4 means that frequencies below 10– 16 Hz contribute the most in characterizing the automaticity of the human gait⁴⁶. In addition to the effects of environment and CLBP, individuals with CLBP may lose gait automatism and require high cognitive attention—in structured as well as unstructured environments. From the above, although individuals with CLBP perform compensatory gait loosening strategies as an adaptation to the environment, they may simultaneously increase their cognitive load, leading to chronicity of pain^{4,5}.

Trunk stability of gait is defined as the ability to maintain functional locomotion despite the presence of small kinematic disturbances or control errors³⁴. Individuals with LBP have a deficiency in muscle coordination and reduced precision in the control of trunk movement due to diminished proprioceptive feedback^{47,48}. These factors appear to cause disturbed control and recovery from perturbations and reduced stability^{49,50}. Some studies have reported higher trunk variability and/or lower stability of gait in LBP as in our results, but opposite results showing decreased variability and/or increased stability of trunk movements due to increased trunk stiffness have also been reported in LBP^{2,3,51,52}. Importantly, tight control of gait was mostly reported in studies employing a treadmill. Treadmill walking tends toward less variability and more stability compared to walking on solid ground or in a daily-living setting⁵³. Although increased stiffness may be successful for control of small-amplitude perturbations experienced in the predictable setting of treadmill walking, it may limit the potential for control and recovery from larger perturbations⁴⁹.

For both stability and variability of gait, data in the AP and ML directions showed different trends. Specifically, in the AP direction, stability of gait was impaired, and the variability was not affected by environmental changes; in the ML direction, the variability was affected by environment and CLBP, but the stability was maintained. A previous study reported change in the trunk variability of gait as an adaptation to environment performed to maintain trunk stability¹⁷. A decrease in stability in the AP direction, even though the variability does not change, may indicate less compensation or inadequate compensation³⁰. Dysfunction of the agonist/ antagonist in the lumbar extension also impedes motor

adaptation of perturbation^{54,55}. Therefore, in the AP direction, individuals with CLBP may have difficulty adapting to the environment, resulting in decreased stability in unstructured daily living. On the other hand, in the ML direction, the stability of gait can be maintained by adaptations to the environment via changes in variability. These results were associated with subjective intensity of pain and fear of movement and were more pronounced in daily living. In addition, trunk stability of gait in the AP direction was related to physical disability in daily living. Previous studies have shown that pain and/or fear promote changes in the sensory-motor control system and movement strategy^{56,57}. Changes in gait control modified by pain and/or fear of movement may disturb a person's adaptation to their environment.

In terms of the present study's limitations, it should be considered that the sample size was relatively small, meaning that the results presented here should be interpreted with caution. In addition, because the questionnaires about pain and fear of movement were not assessed separately in the laboratory and daily living, they may have tended to reflect the pain experienced in the daily-living setting.

In conclusion, we revealed that individuals with CLBP undergo changes in trunk variability and stability of gait depending on the environment and that these changes are related to pain and fear, quality of life. Interestingly, in the AP direction, stability of gait was impaired, and the variability was not affected by environmental changes; in the ML direction, the variability was affected by environment, but the stability was maintained. Although the underlying causes of these different adaptations of gait variability and stability by direction remain to be investigated, we suspect changes in muscle and/or sensory-motor control system. Evaluation of such adaptations to environment in CLBP will enhance our understanding of changes in sensory-motor control by pain and/or fear, and provide information for clinical decision-making and intervention development.

Declarations

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Conflict of interest statement:

The authors have no conflicts of interest to declare.

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Tables

Due to technical limitations, table 1 and table 2 are only available as a download in the Supplemental Files section.

Figures

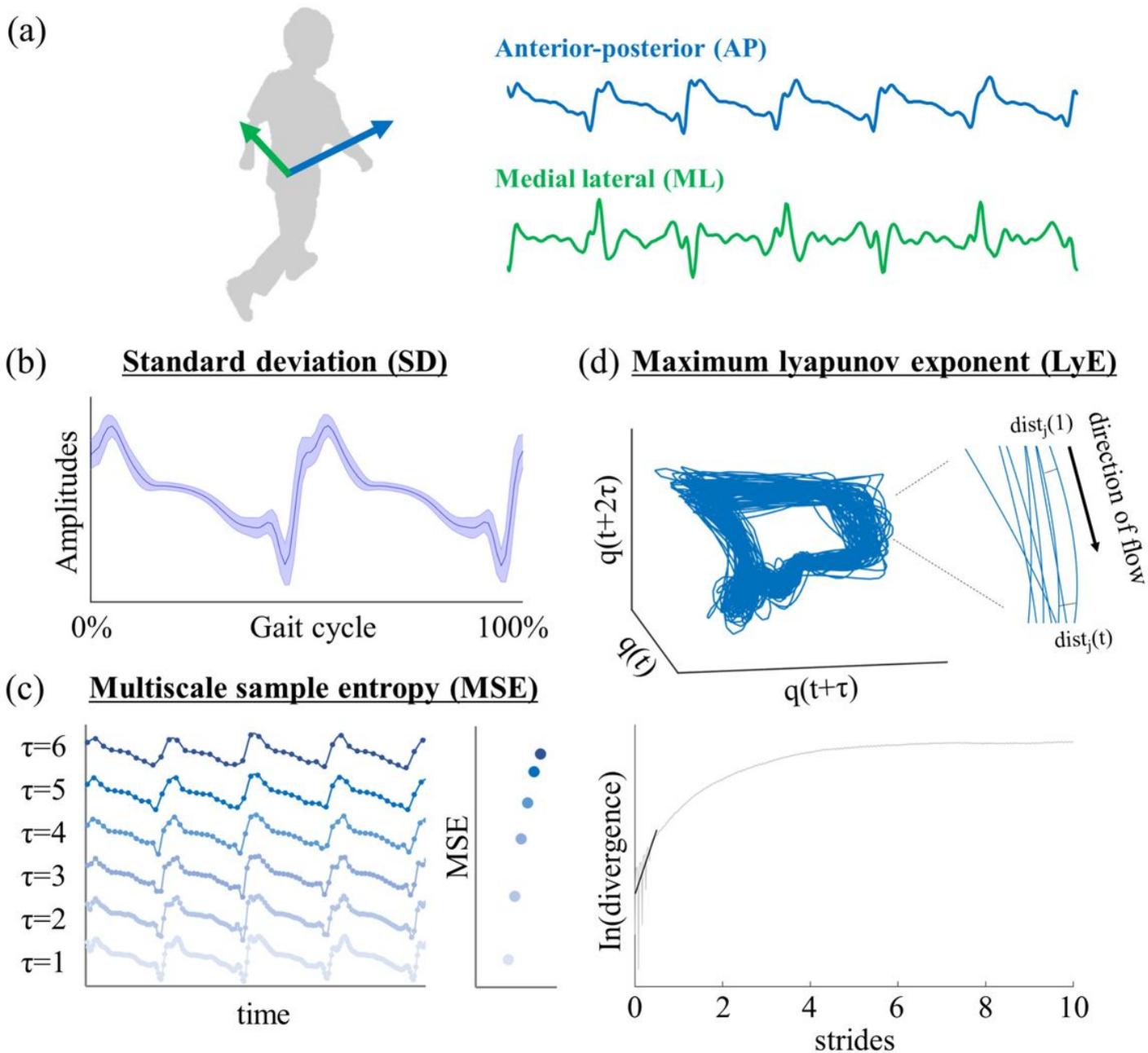


Figure 1

Calculation of gait parameters. (a) Direction of acceleration during gait. Blue line, anterior-posterior (AP), Green line, medial lateral (ML) direction. (b) Stride-to-stride standard deviation (SD); x axis, gait cycle (0-100%); y axis, amplitudes of AP direction. (c) Multiscale sample entropy (MSE). Time scales τ from 1 to 6 represent averages of a successively increasing number of data points in nonoverlapping windows. ($\tau = 1-6$: from light blue to deep blue) The time series of $\tau = 1$ shows original data. (d) The maximum Lyapunov exponent (LyE). A three-dimensional attractor (state space reconstruction of q) and close-up view of part of the attractor. For each point on the attractor, the nearest neighbour was calculated, and divergence of these points was calculated as $dist_j(t)$. The average logarithmic rate of divergence, from which maximum Lyapunov exponents were determined.

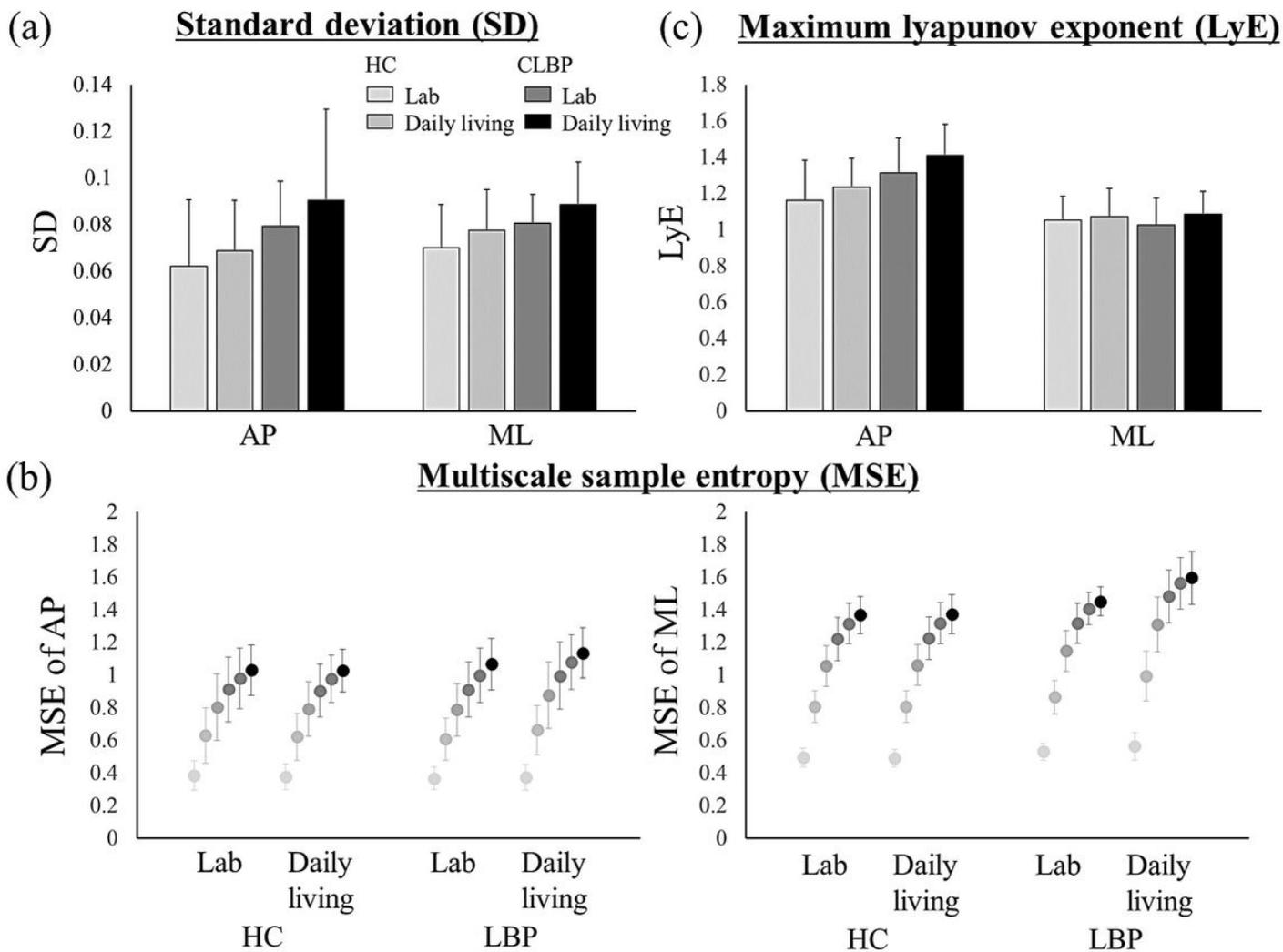


Figure 2

Trunk variability and stability of gait in laboratory and daily-living settings for HC and CLBP groups. (a) Stride-to-stride standard deviation (SD). From left to right: laboratory and daily-living settings in the HC group, laboratory and daily-living in the CLBP group (b) Multiscale sample entropy (MSE). Time scale τ values are represented by grey scale ($\tau = 1-6$: from light gray to black). (c) The maximum Lyapunov exponent (LyE).

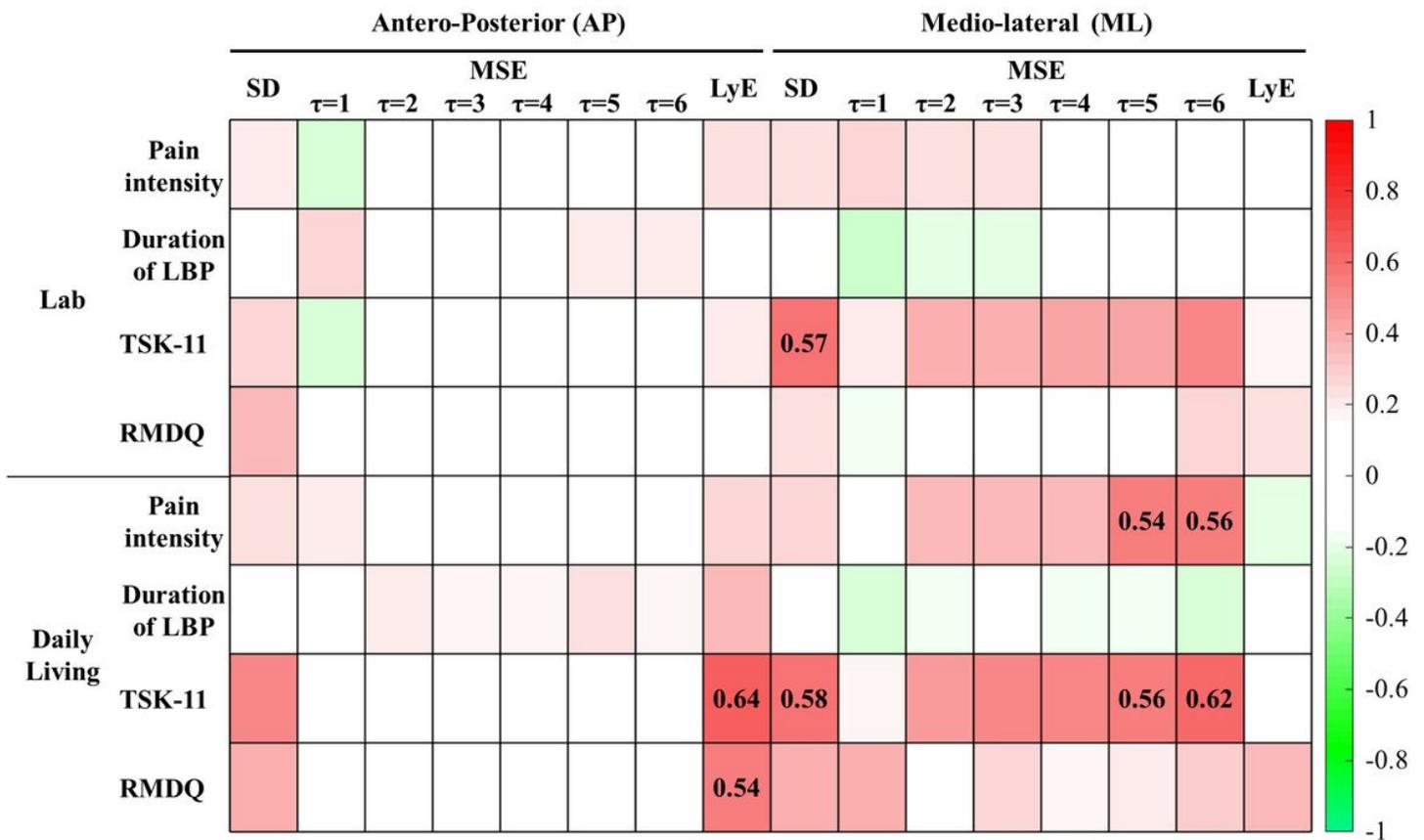


Figure 3

Heat map showing correlation coefficients between trunk motor controls of gait and symptoms of CLBP in the CLBP group. Darker pixels reflect higher correlation values (red positive, green negative). The r value is indicated only in the pixels when the correlation was significant at $p < 0.05$ using Holm corrections.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Table1.xlsx](#)
- [Table2.xlsx](#)