Effect of exercise-induced muscle fatigue on reaction times under postural perturbation conditions in individuals with and without chronic low back pain

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Abstract

**Background:** Total reaction time (TRT), composed of premotor time (PMT) and electromechanical delay (EMD), is susceptible to muscle fatigue and can be affected by pain. However, the muscle fatigue effects of chronic low back pain (cLBP) in postural perturbation conditions have not been adequately reported. This study aimed to examine the impact of pain and muscle fatigue on reaction time, so as to gain insights into the neuromuscular control strategy changes associated with muscle fatigue effect of cLBP.

**Methods:** Twenty-five subjects with cLBP (cLBP group) and twenty-three healthy individuals (HC group) were tested by Biering-Sorensen Test to generate exhaustive muscle fatigue. TRT, PMT and EMD were recorded by surface electromyography during the arm raising task with visual cues prior to and following muscle fatigue. The mean difference (MD) of reaction time was calculated before and after muscle fatigue, denoted as MD\_TRT, MD\_PMT, and MD\_EMD, respectively. Besides, the fear avoidance beliefs questionnaire (FABQ) and visual angle scores (VAS) was evaluated before muscle fatigue in cLBP group.

**Results** The TRT and PMT were significantly prolonged after muscle fatigue in the cLBP group compared with before muscle fatigue (Z=-3.371, \( P=0.001 \); Z=-3.286, \( P=0.001 \), respectively). Meanwhile, the cLBP group had significantly shorter TRT and PMT before muscle fatigue than HC group (Z=-3.299, \( P=0.001 \); Z=-3.256, \( P=0.001 \), respectively). Additionally, the correlation analysis manifested that MD\_PMT and MD\_TRT were positively correlated with FABQ (r=0.422, \( P=0.040 \); r=0.418, \( P=0.042 \)) and VAS (r=0.546, \( P=0.006 \); r=0.564, \( P=0.004 \)) separately.

**Conclusions** The reaction time would be altered by chronic pain in neuromuscular control processes, and muscle fatigue could further induce it delay. Besides, this reaction time delay was positively correlated with pain level and fear-avoidance beliefs. These findings highlight the importance of the muscle fatigue effects with cLBP, such as avoiding exhaustive muscle fatigue and paying more attention to fear-beliefs and pain during rehabilitation.

**Trial registration:** This trial is registered at chictr.org.cn, number ChiCTR2300074348. Registered August 4, 2023.

Background

Chronic low back pain (cLBP) is one of the leading causes of years lived with disability (YLDs), affecting individuals across of all ages and imposing a substantial disease burden on global healthcare system[1]. Non-specific chronic low back pain (NCLBP) accounting for approximately 90% of all cases[2, 3]. However, the pathogenesis of this category population remains unclear, and the current treatment options often yield unsatisfactory[4]. Therefore, it deserves to further explore the underlying mechanisms and associated risk factors of NCLBP.

Exercise-induced muscle fatigue is a common phenomenon in daily life, which refers to the inability of muscles to maintain the expected strength and specific level of function during any physical activity[5]. Exercise-induced muscle fatigue can impact the neuromuscular control of the body[6], leading to changes such as altered proprioceptive sensitivity, weakened muscle contraction function, decreased postural stability. These changes may contribute to the occurrence of chronic pain[7]. For instance, one study has demonstrated that inducing isolated fatigue in the back and hip joints can reduce sagittal postural stability in individuals with NCLBP, as opposed to healthy individuals. It also suggested that muscle fatigue is able to cause the recurrence of low back pain[8]. Further, studies have indicated that muscle fatigue is a common phenomenon in cLBP patients, with an
incidence ranging from approximately 26 to 69.7%[9, 10]. Hence, investigating the role of muscle fatigue may contribute to a deeper understanding of cLBP.

The neuromuscular response process could be altered under conditions of fatigue[11], and prolonging it can decrease the postural control ability as well as increase the risk of physical injury[12]. Total reaction time (TRT), which measures the time taken to respond to various stimulus disturbances, is considered a reliable indicator of the velocity and efficiency of the neuromuscular response process[5]. TRT is comprised of two components: premotor time (PMT) and electromechanical delay (EMD). PMT represents the time interval from stimulus onset to muscle electrical signal generation and may be correlated with pain[13] as well as fear beliefs[14]. It has been suggested that PMT has cognitive and psychological components[5, 15]. EMD is the time from muscle electrical signal excitation to the onset of muscle mechanical contraction, representing the process from myoelectric activation to muscle force production. The length of EMD is closely related to exercise training[16], muscle activity and metabolism[17, 18]. Studying these phases separately can help clarify the specific process of neuromuscular reaction in response to the various stimuli of different circumstances, which is applicable to muscle fatigue and chronic pain research. For instance, a prior investigation has demonstrated that athletes with cLBP required longer PMT and TRT to adapt fatigue when performing a choice reaction time task, in contrast to healthy athletes [19]. Another study examining the effects of fatigue on patellar tendon reflex responses in males and females also found that the TRT (especially in EMD period) was significantly increased in females after fatigue but not in males[20]. These studies suggest that reaction time is not only affected by muscle fatigue but also by the presence of chronic pain. Nevertheless, the muscle fatigue effects on reaction time in cLBP under postural perturbation conditions has seldomly reported. It remains unclear whether the alterations of neuromuscular reaction time caused by muscle fatigue are associated with pain perception and fear-related beliefs.

As noted previously, we propose the scientific hypothesis that individuals with cLBP would experience reaction time change due to muscle fatigue when faced with postural perturbations, and these changes might be correlated with pain-related fear beliefs. In this research, surface electromyography (s-EMG) was used to measure the reaction time before and after exercise-induced muscle fatigue under postural perturbation condition, aiming to explore the inter-relationships between pain, muscle fatigue, and reaction time in individuals with and without cLBP. Through this endeavor, this study would further reveal the theoretical basis for muscle fatigue effects of neuromuscular control strategy in cLBP.

**Methods**

**Study design and setting**

This cross-sectional study was approved and supervised by the Ethics Committee of the First Affiliated Hospital, Sun Yat-sen University (Ethics Approval No. [2023] 386-1), registered in the China Clinical Trial Registry Center (No. ChiCTR2300074348), and conducted by the Department of Rehabilitation Medicine. The Declaration of Helsinki and all human experimentation rules were respected[21]. Subjects were informed of the potential risks (e.g., electrode pad allergy, muscle soreness) and their consents were obtained before the trial. In order to maintain the quality of the report, we followed the STROBE standards and checklist[22].

**Participants**
Subjects were recruited through advertisements and screened by a professional physician. The inclusion criteria of cLBP group were as follows: 1) in agreement with the medical diagnoses for NCLBP[23]; 2) age between 18 and 59 years; 3) pain was located between the 12th rib and the gluteal sulcus, the symptom lasted more than 3 months, and with at least one episode recurrent low back pain in the past 3–12 months; 4) the VAS score were greater than 3/10 points; 5) right-dominated hand; 6) the subjects in health group were matched with cLBP group for general epidemiologic characteristics such as age, gender, height, weight, education level, and body mass index.

The tips of exclusion criteria were: 1) specific low back pain (e.g., spinal tumor, tuberculosis, fracture, spinal stenosis, intervertebral disc herniation.); 2) history of spinal or pelvic surgery within the past two years; 3) undergoing low back pain physical rehabilitation or oral medication; 4) body mass index above 30 kg/m\(^2\); 5) pregnant or preparing for pregnancy. 6) unable to cooperate with the examination on account of serious cognitive psychological or with audiovisual disorders.

**Sample size calculation**

In the preliminary study, we applied the TRT parameter changes (before vs after muscle fatigue) of eight subjects, and compared the results between cLBP (0.1642 ± 0.0835) and HC (0.1049 ± 0.0485). These data were then used to conduct the sample calculation by G-Power (version 3.1.9.4). The Cohen's d value was 0.868, using two-sided test with \( \alpha = 0.05 \), power(1-\( \beta \)) = 0.8, and allocation ratio(N1/N2) = 1. The sample size was calculated to be 44 and 22 in each group. Considering a 10% sample dropout rate, the final sample size in the study was approximately 50 and 25 in each group.

**Instruments and Measures**

In this trial, s-EMG was employed to gauge reaction time under dynamic postural perturbation conditions before and after muscle fatigue. The visual angle scores (VAS) and fear-avoidance beliefs questionnaire (FABQ) were used to assess pain perception and fear-avoidance beliefs in cLBP.

**Biering-Sorensen Test**

The Biering-Sorensen Test (BST) is a well-established and commonly used paradigm to induce muscle fatigue. It is considered reliable, valid, and safe, and has been used in numerous studies involving individuals with low back pain[24]. In this study, we used the BST to induce muscle fatigue in all subjects. The details were as follows: the subject lay prone on a treatment bed, and the parts below the iliac spine were fastened with belt at the hip, popliteal fossa, and ankle level. In the meantime, the parts above the iliac spine were suspended outside the treatment bed. Once the test started, subjects were instructed to cross over upper limbs to the chest and keep their body in a horizontal line. The test was ended when subjects were too exhausted to persist or experienced pain. The duration time of Biering-Sorensen Test (BST-DT) was recorded immediately, and a rapid dynamic postural perturbation test was performed within 20 seconds[25].

**Dynamic postural perturbations test**

The rapid arm-raising test (ART) was executed to detect dynamic postural perturbation in all subjects both before and after muscle fatigue. The ART is a reliable internal dynamic postural perturbation paradigm, and we slightly modified it referring to previous research[26]. The detailed process of ART unfolded as follows: subjects stood barefoot on a pressure platform with their hands naturally hanging down. A visual arm-raising signal (depicted as
a solid black circle lasting for a duration of 3 s), compiled by Psychopy software (version 2022.1.3), was presented on the monitor which was placed 2 meters in front of subjects at the eye level. In this procedure, the signal was presented three times in 30 s randomly. Once it arose, the subject was instructed to raise their right arm to the shoulder plane as quickly and explosively as possible, and return to the neutral position when the signal disappeared. In order to ensure subjects were familiar with the test, they were given two or three opportunities to practice the procedure before the data collection.

**Reaction time test**

The wireless s-EMG technology (Trigno™, Delsys Incorporated, USA), represents a prevalent method to detect neuromuscular reaction time, and we used it to record PMT, EMD and TRT, sperately[5, 27]. Through technical modification in this study, the physical impulses emitted from Psychopy software would simultaneously trigger the acquisition of the s-EMG, which realized the absolute synchronous recording between ART signals and s-EMG acquisition. The specific process was as follows: the s-EMG electrodes were placed on the anterior deltoid muscle (before placing the electrodes, the skin keratin and dirt was removed by scrub cream, and then cleaned with 75% alcohol to reduce the impedance). The moment that the ART signal appeared in the monitor was designated as T₀. The onset time of the initial mechanical contraction moment was recorded through displacement sensor in s-EMG, which was denoted as \( T_{\text{torque}} \). Meanwhile, the time point of the myoelectrical activation was characterized as \( T_{\text{electrical}} \). TRT, calculated as the difference between \( T_{\text{torque}} - T_0 \), represented the time interval from the appearance of ART signal to the mechanical contraction moment. PMT was determined by the computation \( T_{\text{electrical}} - T_0 \), referring to the time interval from the appearance of ART signal to the myoelectrical activation moment. EMD was the time interval from the myoelectrical activation to mechanical contraction moment, which was computed through the equation \( T_{\text{torque}} - T_{\text{electrical}} \). Besides, we calculated the mean difference (MD) change of TRT, PMT and EMD before and after muscle fatigue, which were denoted as \( \Delta \text{TRT} \), \( \Delta \text{PMT} \) and \( \Delta \text{EMD} \), respectively.

**Pain and fear-avoidance belief assessment**

VAS and FABQ demonstrate a good reliability and validity to assess the degree of pain and fear-avoidance beliefs on daily activities and work in cLBP[28, 29]. The VAS scores range from 0 to 10, with higher scores indicating more severe pain. Specifically, the scale encompasses categories such as: absence of pain (0), mild pain (1 ~ 3), moderate pain (4 ~ 6), and severe pain (7 ~ 10). The FABQ consists of 16 items, in which 5 items assess the fear avoidance beliefs related to the impact of physical activity on chronic pain, the other 11 items refer to work-related activities. The total score of FABQ is 96, each item ranging from 0 to 6 points. Elevated scores on FABQ represent a higher degree of fear-avoidance beliefs. In this trial, we obtained VAS and FABQ scores through electronic questionnaire in cLBP group before muscle fatigue.

**Bias**

To ensure the mitigation of measurement errors and result biases, meticulous quality control measures were implemented, encompassing the following aspects: 1) a comprehensive explanation of the assessment procedure was provided to enhance collaboration among participants and researchers; 2) the same evaluator who was blinded with this study performed the assessment; 3) the average reaction time of three ART measurements was included for final data analysis. 4) additionally, the ART signal was fully synchronized with
the s-EMG acquisition through meticulous technique refinement, which effectively controlled the acquisition bias of reaction time.

**Data processing and statistical analysis**

We employed Matlab R2022a software (MathWorks, Natick, MA, USA) to process and analyze the s-EMG signals. Subsequent statistical analysis was performed by SPSS 20.0 (IBM, Chicago, USA). Normality test was processed first for all continuous variables (age, height, weight, BMI, TRT, PMT, EMD, VAS, FABQ, BST-DT). The result was expressed as mean ± standard deviation (MD ± SD) when the data adhered to a normal distribution. The paired t-test was used for comparisons within groups, and the independent t-test for comparisons between groups. In cases where the data deviated from a normal curve, the results were represented by median (25%, 75% interquartile values) and non-parametric tests were used for inter- and intra-group comparisons. Pearson or Spearman was used to analyze the correlation of MD\textsubscript{TRT}, MD\textsubscript{PMT}, and MD\textsubscript{EMD} with the VAS and FABQ separately, based on normality test results of this data. p < 0.05 indicates a statistical significance.

**Results**

**Demographic Characteristics and research flowchart**

The present study initially enrolled a total of 49 participants, including 24 healthy individuals (HC group) and 25 cLBP subjects (cLBP group). One healthy subject withdrew from the trial due to personal reasons, resulting in a final participant count of 48.

As shown in Table 1, no significant differences were observed in baseline characteristics between the two groups, such as gender, age, weight, BMI, height, education level. In addition, The VAS, FABQ scores and BST-DT of cLBP group were also exhibited in Table 1. Furthermore, the pertinent experimental paradigms and the research flowchart of this study were illustrated in Figure 1. In specific, Figure 1-A depicted the schematic diagram of arm-raising test (ART); Figure 1-B illustrated the schematic diagram of the muscle fatigue test (Biering-Sorensen Test, BST), and Figure 1-C presented the flow chart of the study design and procedures.

Table 1 Demographic variables of the subject's data
<table>
<thead>
<tr>
<th></th>
<th>HC (n=23)</th>
<th>cLBP (n=25)</th>
<th>t/χ²/Z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender male/female a</td>
<td>10/14</td>
<td>10/15</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>Age years c</td>
<td>29.35(23.00, 33.00)</td>
<td>31.56 25.00, 36.00</td>
<td>-1.20</td>
<td>0.23</td>
</tr>
<tr>
<td>Weight (kg) b</td>
<td>62.20±11.76</td>
<td>58.72±10.29</td>
<td>1.09</td>
<td>0.28</td>
</tr>
<tr>
<td>Height (m) b</td>
<td>1.64±0.07</td>
<td>1.66±0.08</td>
<td>-0.83</td>
<td>0.41</td>
</tr>
<tr>
<td>BMI (kg/m²) b</td>
<td>22.98±3.73</td>
<td>21.17±2.55</td>
<td>1.97</td>
<td>0.06</td>
</tr>
<tr>
<td>Education level c</td>
<td>Juniors college or less</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>undergraduate</td>
<td>5</td>
<td>9</td>
<td>-1.59</td>
</tr>
<tr>
<td></td>
<td>Postgraduate or higher</td>
<td>17</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>BST-DT (s) b</td>
<td>100.13±34.95</td>
<td>105.08±36.83</td>
<td>-0.48</td>
<td>0.64</td>
</tr>
<tr>
<td>VAS</td>
<td></td>
<td>5.28±1.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FABQ (score) b</td>
<td></td>
<td>47.33±18.43</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** a Value is presented as sex composition ratio. b Values are presented as mean ± standard deviation. c Value is presented as median (25%~75% interquartile range).

**Abbreviations:** BST-DT, duration time of Biering-Sorensen Test; VAS, visual angle scale; FABQ, Fear Avoidance Beliefs Questionnaire.

**The reaction time change before and after exercise-induced muscle fatigue**

Following muscle fatigue induction, both TRT and PMT were significantly prolonged in cLBP group (Z=-3.371, \( P=0.001 \), \( \chi^2=0.751 \), Cohen's \( d=3.471 \); \( Z=-3.286 \), \( P=0.001 \), and \( \chi^2=0.750 \), Cohen's \( d=3.467 \), respectively). However, no statistical differences were observed in EMD within the cLBP group, nor in TRT, PMT, and EMD within the HC group.

Furthermore, before inducing muscle fatigue, both TRT and PMT were significantly decreased in cLBP group compared to HC group (Z=-3.299, \( P=0.001 \), \( \chi^2=0.750 \), Cohen's \( d=3.467 \); \( Z=-3.256 \), \( P=0.001 \), \( \chi^2=0.750 \), Cohen's \( d=3.465 \), respectively). Nevertheless, no statistical differences were observed neither in EMD before muscle fatigue, nor in TRT, PMT, and EMD after muscle fatigue. The details were presented in Table 2.

Table 2 Comparison of PMT, EMD and TRT between two groups
In order to assess the change degree of reaction time before and after muscle fatigue in cLBP group, we calculated the mean difference (MD) of TRT, PMT, and EMD (referred to as $\text{MD}_{\text{TRT}}$, $\text{MD}_{\text{PMT}}$, and $\text{MD}_{\text{EMD}}$, respectively). Correlation analysis revealed that $\text{MD}_{\text{TRT}}$ and $\text{MD}_{\text{PMT}}$ manifested positive correlations with FABQ ($r=0.418$, $P=0.042$; $r=0.422$, $P=0.040$, respectively), and similarly exhibited positive correlations with VAS ($r=0.546$, $P=0.006$; $r=0.564$, $P=0.004$, respectively). The details were exhibited in Table 3.

Table 3 Correlation analysis of $\text{MD}_{\text{TRT}}$, $\text{MD}_{\text{PMT}}$, $\text{MD}_{\text{EMD}}$ and BST-DT with VAS or FABQ

<table>
<thead>
<tr>
<th>Group/Time</th>
<th>Before fatigue</th>
<th>After fatigue</th>
<th>Cohen's $d$</th>
<th>$\eta^2$</th>
<th>$Z/\ P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>0.4078(0.3541,0.5384)</td>
<td>0.4142(0.3473,0.5304)</td>
<td>3.359</td>
<td>0.738</td>
<td>-0.958/0.338</td>
</tr>
<tr>
<td>cLBP</td>
<td>0.3294(0.3010,0.3669)</td>
<td>0.3864(0.3280,0.4441)</td>
<td>3.467</td>
<td>0.750</td>
<td>-3.286/0.001</td>
</tr>
<tr>
<td>Cohen's $d$</td>
<td>3.465</td>
<td>3.459</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta^2$</td>
<td>0.750</td>
<td>0.738</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z/\ P$</td>
<td>-3.256/0.001</td>
<td>-0.938/0.348</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>0.0253(0.0245,0.0259)</td>
<td>0.2052(0.0244,0.0257)</td>
<td>3.334</td>
<td>0.735</td>
<td>-0.373/0.709</td>
</tr>
<tr>
<td>cLBP</td>
<td>0.0252(0.0247,0.0258)</td>
<td>0.0251(0.0247,0.0272)</td>
<td>3.351</td>
<td>0.737</td>
<td>-0.760/0.447</td>
</tr>
<tr>
<td>Cohen's $d$</td>
<td>3.318</td>
<td>3.356</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta^2$</td>
<td>0.733</td>
<td>0.738</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z/\ P$</td>
<td>-0.011/0.992</td>
<td>-0.874/0.382</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>0.4321(0.3800,0.5629)</td>
<td>0.4413(0.3541,0.5384)</td>
<td>3.358</td>
<td>0.738</td>
<td>-0.925/0.355</td>
</tr>
<tr>
<td>cLBP</td>
<td>0.3548(0.3257,0.3926)</td>
<td>0.4107(0.3529,0.4693)</td>
<td>3.471</td>
<td>0.751</td>
<td>-3.371/0.001</td>
</tr>
<tr>
<td>Cohen's $d$</td>
<td>3.467</td>
<td>3.359</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta^2$</td>
<td>0.750</td>
<td>0.738</td>
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<tr>
<td>$Z/\ P$</td>
<td>-3.299/0.001</td>
<td>-0.938/0.348</td>
<td></td>
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</tbody>
</table>

Abbreviations: TRT, total reaction time. PRT, premotor time. EMD, electromechanical delay. $\eta^2$, eta squared.

Correlation analysis between the mean difference (MD) of reaction time and VAS, FABQ

In order to assess the change degree of reaction time before and after muscle fatigue in cLBP group, we calculated the mean difference (MD) of TRT, PMT, and EMD (referred to as $\text{MD}_{\text{TRT}}$, $\text{MD}_{\text{PMT}}$, and $\text{MD}_{\text{EMD}}$, respectively). Correlation analysis revealed that $\text{MD}_{\text{TRT}}$ and $\text{MD}_{\text{PMT}}$ manifested positive correlations with FABQ ($r=0.418$, $P=0.042$; $r=0.422$, $P=0.040$, respectively), and similarly exhibited positive correlations with VAS ($r=0.546$, $P=0.006$; $r=0.564$, $P=0.004$, respectively). The details were exhibited in Table 3.

Table 3 Correlation analysis of $\text{MD}_{\text{TRT}}$, $\text{MD}_{\text{PMT}}$, $\text{MD}_{\text{EMD}}$ and BST-DT with VAS or FABQ

<table>
<thead>
<tr>
<th></th>
<th>$\text{MD}_{\text{TRT}}$</th>
<th>$\text{MD}_{\text{PMT}}$</th>
<th>$\text{MD}_{\text{EMD}}$</th>
<th>BST-DT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$ value</td>
<td>$p$ value</td>
<td>$r$ value</td>
<td>$p$ value</td>
</tr>
<tr>
<td>VAS</td>
<td>0.564</td>
<td>0.004</td>
<td>0.546</td>
<td>0.006</td>
</tr>
<tr>
<td>FABQ</td>
<td>0.418</td>
<td>0.042 *</td>
<td>0.422</td>
<td>0.040 *</td>
</tr>
</tbody>
</table>

Notes: * $P < 0.05$. $\text{MD}_{\text{TRT}}$, $\text{MD}_{\text{PMT}}$, and $\text{MD}_{\text{EMD}}$ were analyzed by Spearman correlation analysis with VAS or FABQ, respectively. BST-DT with VAS or FABQ was analyzed by Pearson correlation analysis.
Correlation analysis between BST-DT and VAS, FABQ

The correlation analysis results showed a lack of significant correlation between BST-DT and FABQ ($r=-0.019$, $P=0.930$) as well as between BST-DT and VAS ($r=-0.350$, $P=0.086$). Further details were provided in Table 3.

Discussion

This study carried out the BST to induce muscle fatigue and performed an ART in response to sudden visual stimulation in people with and without cLBP, and determined the reaction time before and after fatigue. We found that: 1) the TRT and PMT before muscle fatigue were reduced in cLBP group, compared to HC group ($P < 0.05$); 2) following muscle fatigue, the TRT and PMT were prolonged in cLBP group compared with the before muscle fatigue ($P < 0.05$), and 3) the degree of $MD_{TRT}$ and $MD_{PMT}$ were positively correlated with both pain perception and fear-avoidance beliefs.

Chronic pain and reaction time

Reaction time is usually measured by limb movement response to target stimulation[30], reflecting an individual's ability to cope with the danger on sudden perturbation conditions and relying on the integration of sensorimotor, visuospatial skills, and cognitive psychological function[31]. Certain earlier studies have shown that chronic pain can alter the reaction time through affecting cognitive psychological function[32, 33] and motor sensory integration [34-36]. As an example, one study measured hand and foot reaction time in response to light stimulation among individuals with and without chronic neck pain, the results showed that people with chronic neck pain had slower hand and foot reactions along with poorer hand-eye coordination[37]. In addition, another study investigated the impact of chronic musculoskeletal pain on simple and choice foot reaction time in the elderly, indicated that both pain and light interferences contributed to slower foot reaction time, which hindered physical response and increased vulnerability to falls[30]. Furthermore, in relation to trunk reaction time during slip perturbation, a study manifested no significant difference between individuals afflicted with cLBP and those without such pain[38].

Inconsistent with the above research, a study measured the ankle muscle reaction time after inducing slip perturbations on a treadmill, and found that compared with healthy individuals, cLBP exhibited faster reaction time on the dominant tibialis anterior muscles. This suggests that cLBP patients may adopt a dominance-dependent compensatory strategy to enhance dynamic balance control[39]. Additionally, Tomasz Sipko et al. speculated that cLBP patients exhibited shorter preparation time in the sit-to-stand task due to adopting posture compensation strategy[40]. Furthermore, a comprehensive systematic review and meta-analysis draw the conclusion that chronic pain patients, including those with fibromyalgia, had faster reaction time toward pain-related information compared to asymptomatic individuals[41]. In view of the above research, it's reasonable to assume that chronic pain might play an important role in response to sudden postural perturbation, the discrepancy among this research could be attributed to gender and task differences. In the present study, we compared the limb movement responses to sudden postural perturbation in individuals with and without cLBP and found that cLBP had shorter reaction time, which aligns with the findings of prior studies by Sung PS, et al[39] and Sipko T, et al[40], inferring that pain might contribute to hypervigilance or facilitated attention[41]. Besides, we still observed that the shortened reaction time mainly occurred during PMT phase, indicating that this alteration...
might primarily be influenced by the central components of the neuromuscular response process, specifically the cognitive and psychological dimensions.

**Muscle fatigue and reaction time**

Patients with cLBP are more prone to experience exercise-induced muscle fatigue[9]. Meanwhile, some previous studies have highlighted that exercise-induced muscle fatigue might serve as a significant factor to alter the postural control as well as prompt the occurrence or recurrence of low back pain. For example, one study performed by Allison GT et al. using bilateral arm raising test to conduct postural perturbation, found that the anticipatory response of external oblique muscle would be facilitated after trunk extensor muscle fatigue, and declared that the activation latency change of the trunk postural muscles caused by fatigue may be related to the occurrence of low back pain[42];

Furthermore, by inducing abdominal muscle fatigue, Allison GT et al. also found that the magnitude of muscle activity during anticipant postural adjustments was decreased about 20% in both rectus abdominis (fatigued muscle) and erector spinae (not fatigued), and they implied this muscle activity might rely on central fatigue effect[43]. In our study, we observed the TRT of cLBP were significantly prolonged after local lumbar back muscle fatigue, especially in PMT phrase. These observations indicated that 1) muscle fatigue caused a negative impact on cLBP to cope with sudden postural perturbation; 2) PMT seemed to carry more weight in the whole reaction time. For this issue, the extension in reaction time could be attributed to the fact that muscle fatigue brings about alterations in cognitive and psychological processes[44, 45]. Hence, we have reason to deem that fatigue is not an independent or limited factor in the central and peripheral system, and the relationship is intricate and mutually influential, aligning with the viewpoint of Morris SL, et al.’s research[43].

Interestingly, the pre-muscle fatigue TRT, PMT and EMD were not significantly different from post-muscle fatigue in HC group. We considered that this could be attributed to the ample neural resource capacity inherent in healthy individuals[46]. Even under conditions of fatigue, they possess adequate neural resources to effectively address abrupt perturbations, negating the need for alterations in reaction time, as also described by Le Mansec Y et al[5]. Additionally, we also noted that both the pre- and post-muscle fatigue EMD remained unaltered in individuals with and without cLBP. Notably, some previous similar studies have yielded different results. For example, Sajjad Abdollah et al.’s[19] study revealed that the EMD of lower limb muscles (gastrocnemius, tibialis anterior, and semitendinosus) in basketball players with cLBP had changed through inducing lower limb muscle fatigue. Furthermore, another study performed intermittent isometric knee flexions at 60% of the maximum voluntary contraction until failure, and demonstrated that fatigue training resulted in shorter EMD of knee muscles (biceps femoris, semitendinosus, etc.) in healthy individuals with higher training status[47]. The reason for the discrepancy between our research and aforementioned study might be attributed to the target observe muscle was different. Specifically, the target muscles in the cited studies were subjected to fatigue load, resulting in altered EMD. Conversely, the deltoid muscle was not undergoing fatigue load in our study, likely contributing to the stability of EMD. In other words, EMD is the time interval between muscle electrical signal excitation and muscle torque signal generation, and is more closely related to local tissue metabolic changes[48], while the deltoid muscle was undistributed by fatigue load in our research, which might be the reason why EMD remained stable.

**Pain related fear-avoidance and reaction time**
The patients with cLBP often accompany a certain degree of pain-related fear beliefs, and the severity of these beliefs is closely associated with reaction time delay. As an illustration, one previous study, executing a seated rapid arm flexion in self-initiated and cued conditions, found that the delay of postural adjustments time was correlated with fear-avoidance beliefs in cLBP[49]. Similarly, another study focusing on reaction time under dual-task conditions (performing an auditory task while receiving electrical stimulation) demonstrated that the reaction time was prolonged more obviously in cLBP, compared to asymptomatic individuals. Moreover, regression analyses unveiled that high pain-related fear was associated with reaction time delay[50].

As previously stated, the change of reaction time was correlated with pain-related fear beliefs as well as ascribed by muscle fatigue effect. However, it has not been clearly reported whether the changes of reaction time induced by muscle fatigue are related to pain-related fear beliefs. In this study, through observing changes of reaction time before and after muscle fatigue in cLBP and performing correlation analysis with pain and fear-avoidance beliefs, we identified a positive correlation between MD\textsubscript{TRT} and MD\textsubscript{PMT} with VAS and FABQ separately. The results suggest that pain and fear-avoidance beliefs might serve as cognitive and psychological mechanism for reaction time delay during the fatigue process. Besides, BST-DT was exhibited no significant differences between cLBP and healthy individuals, and also no correlation with VAS and FABQ. We attributed this phenomenon to the fact that participants in our study were relatively young and often possessed better self-efficacy. They were willing to regard the difficult tasks as a challenge rather a danger to avoid, which is in echo with the perspectives of Vincent HK et al.’s study[51].

**Limitations**

This study still has certain limitations. Firstly, we didn't investigate the muscle fatigue effects of BST on trunk muscles, such as rectus abdominis, oblique muscles, and transversus abdominis, etc. Future research should aim to explore the response time on trunk muscles, which will contribute to a better understanding the potential mechanism of reaction time alteration induced by muscle fatigue. Secondly, the lack of central function assessment of reaction time in our research could be addressed by incorporating brain function devices, such as electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS). This integration will further enhance the understanding of neuromuscular processes. Lastly, we only observed simple reaction time and didn't investigate other types of reaction time such as discrimination reaction time or choice reaction time. Future study would focus on reaction time mentioned above from the perspective of cognitive load, which might be conductive to comprehend the relationship between muscle fatigue and reaction time.

**Conclusions**

This study measured the reaction time under postural perturbation conditions before and after exercise-induced muscle fatigue in individuals with and without cLBP, and also conducted the correlation analysis between the degree of reaction time changes and pain-related fear-avoidance beliefs. The study's results unveiled that both pain and muscle fatigue could alter the reaction time during neuromuscular control process, and these changes relied more on the pre-motor time which was mainly composed of cognitive and psychological aspects. These findings would shed light on better understanding of the potential relationship between exercise-induced muscle fatigue and cLBP, and indicate that more attention need to be paid on muscle fatigue effects, which could enhance the systematic management of cLBP.
Abbreviations

cLBP: chronic low back pain; TRT: total reaction time; PMT: pre-motor time; EMD: electromechanical delay; MD: mean difference; s-EMG: surface electromyography; ART: Arm-raising test; BST: Biering-Sorensen Test; FABQ: fear-avoidance beliefs questionnaire; VAS: visual analogue scale; BST-DT: duration time of Biering-Sorensen Test.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the First Affiliated Hospital, Sun Yat-sen University (Ethics Approval No. [2023] 386-1) and registered in the China Clinical Trial Registry Center (No. ChiCTR2300074348). All the participants gave their informed consent.

Consent for publication

Consent for publication of individual data has been obtained from all the participants of the study.

Availability of data and materials

The data are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no conflicts of interest regarding this study.

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Authors’ contributions

XWW, PJH and WCH conceived the study; XWW, LZF and HZM performed data collection and statistical analysis; XWW and PJH drafted the manuscript; XHY, YHC and MHA revised the manuscript; XH assisted in recruiting subjects. All authors read and approved the final manuscript.

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References


**Figures**

![Figures](image)

**Figure 1**

Experimental paradigm and the test flow chart

**Notes:** Figure 1-A, schematic diagram of the arm-raising test (ART) task with visual cued was illustrated. Figure 1-B showed schematic diagram of the Biering-Sorenson Test (BST). Figure 1-C showed the flow chart of this trial.