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Impact of lumbar delayed-onset muscle soreness on postural stability in standing postures

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ABSTRACT

Background: Similar impact on proprioception has been observed in participants with lumbar delayed-onset muscle soreness (DOMS) and chronic low back pain (LBP), raising questions about the relevance of lumbar DOMS as a suitable pain model for LBP when assessing back pain-related postural stability changes.
Research question: Does lumbar DOMS impact postural stability?
Methods: Twenty healthy adults participated in this experimental study and underwent a posturographic examination before and 24 to 36 h after a protocol designed to induce lumbar DOMS. Posturographic examination was assessed during quiet standing on both feet with eyes opened (EO), with eyes closed (EC), and on one-leg (OL) standing with eyes opened. Postural stability was assessed through center of pressure (COP) parameters (COP area, velocity, root mean square, mean power frequency) which were compared using repeated measure ANOVA. Moreover, pain, soreness and pressure pain threshold (PPT) on specific muscles were assessed.
Results: There was a significant main effect of the postural condition on all COP variables investigated. More specifically, each COP variable reached a significantly higher value in the OL stance condition than in both EO and EC bipedal conditions (all with $p < 0.001$). In addition, the COP velocity and the mean power frequency along the anteroposterior direction both reached a significantly higher value in EC than in EO ($p < 0.001$). In contrast, there was no significant main effect of the DOMS nor significant DOMS X postural condition interaction on any of the COP variables. There was a significant decrease in the PPT value for both the left and right erector spinae muscles, as well as the left biceps femoris.
Significance: Lumbar DOMS had no impact on postural stability, which contrasts findings in participants with clinical LBP. Although DOMS induces similar trunk sensorimotor adaptations to clinical LBP, it does not appear to trigger similar postural stability adaptations.

1. Introduction

Delayed-onset muscle soreness (DOMS) can be described as a spectrum of discomfort, ranging from slight muscle stiffness to severe incapacitating pain [1]. This sensation can be attributed to the muscular damage and inflammation induced by eccentric contractions or unusual intense activities [1,2]. DOMS can persist over the course of several days [3], typically peaking within 24 to 72 h [1,4]. Additionally, DOMS frequently yields decreased muscle function, including weakened strength, reduced range of motion, and decreased proprioception [5–7].

Individuals experiencing recurrent or chronic nonspecific low back pain (LBP) exhibit a decrease in proprioception within their lumbar muscles, similar to those observed with DOMS [8,9]. Such similarities coupled with comparable psychological factors such as fear of movement and pain catastrophizing, establish DOMS as a relevant pain model to effectively replicate the alterations typically observed in clinical LBP

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such as altered postural stability [6,7,10].

According to a recent meta-analysis [11], individuals with chronic LBP demonstrated a decrease in postural stability. This decrease in stability, quantified through the displacement of the center of pressure (COP) during quiet standing, is more pronounced in the absence of visual cues [11] and persist during more unstable conditions such as the one-leg (OL) stance condition [12]. These findings could be attributed to a reduction in proprioceptive feedback originating from the lumbar muscles [9,13], as the maintenance of stable balance relies on the integration of sensory inputs from visual, vestibular, and proprioceptive systems [14].

To explore if lumbar DOMS is a viable pain model for investigating neuromuscular adaptations associated with clinical LBP, it is essential to evaluate whether low back DOMS can accurately reproduce clinical motor adaptations, such as modified postural stability during conditions involving quiet standing with both eyes open (EO) and eyes closed (EC), as well as OL stance condition. The primary objective of this study was to investigate the impact of lumbar DOMS on postural stability, assessed through the displacement of COP. It was hypothesized that, with lumbar DOMS, participants will exhibit decreased postural stability during quiet standing, particularly when visual cues are removed. Additionally, it was expected that these effects would be more pronounced during challenging conditions such as the OL stance.

2. Materials and methods

2.1. Participants

Twenty healthy participants (13 males and 7 females) were included in this experiment (cf. Table 1 for details on the anthropometrical characteristics). A total of 19 participants was required to achieve a statistical power of 0.8 and an alpha of 0.05 for a two-way repeated measures (RM) ANOVA (levels: 3 by 2) with a moderate effect size of $f = 0.25$. Exclusion criteria were as follows: lumbar or lower limb pain episodes or injury during the year preceding the experiment, soreness in the lower limbs or back muscles, and inflammatory arthritis or spinal surgical history. The project received approval from the Research Ethics Board for human research of the “Université du Québec à Trois-Rivières” N° CER-23–297-07.05 and complies with the principles in the Declaration of Helsinki. All participants gave written informed consent.

2.2. Experimental protocol

Participants participated in two experimental sessions, which were separated by 24 to 36 h. In the first session, participants completed the physical activity questionnaire developed by the National Observatory of Physical Activity and Sedentariness (ONAPS-PAQ) and the Tampa scale of kinesiophobia (TSK) questionnaires. Following this assessment, the pressure-pain threshold (PPT) of specific trunk and leg muscles were measured. Once these different tests were completed, participants were asked to perform a series of postural conditions on a force plate to evaluate their postural sway. These tests were followed by the DOMS protocol. In the second session, participants were asked about the level of their perceived pain and soreness and performed the same tests as in the first session, except that the questionnaires and DOMS protocol were not repeated. (Fig. 1.).

Table 1
Anthropometrical characteristics of participants, along with ONAPS-PAQ and TSK questionnaires.

Outcome	Participants (n = 20) Mean (SD)
Age (years)	26.70 (5.04)
F:M	7:13
Weight (Kg)	66.95 (19.91)
Height (m)	1.73 (0.09)
BMI (kg/m^2)	22.33 (5.74)
Leg dominance (R:L)	14:6
ONAPS Physical activity (METs.min/week)	5254.45 (4560.69)
ONAPS Physical activity classification	Active +
ONAPS Sedentary behavior (hours/day)	8.46 (3.03)
ONAPS Sedentary behavior classification	High level of sedentary behavior
TSK	25.3 (6.44)
TSK classification	Low level of kinesiophobia

2.3. Questionnaires

Participants completed the validated French version [15] of the ONAPS-PAQ questionnaire to evaluate their level of physical activity and sedentary lifestyle during a typical week. Moreover, they completed the French version of the TSK questionnaire to assess their fear of movement or injury [16]. Both questionnaires were administered at the beginning of the first session. The corresponding mean values for both questionnaires are presented in Table 1.

2.4. Postural conditions

Participants stood upright and barefoot on a force plate (Bertec Corp, Columbus, OH, USA) that collected the 3D ground reaction forces and moments. Participants performed the three following postural conditions:

1. Quiet standing on both feet with EO while keeping their arms by their sides (EO condition).
2. Quiet standing on both feet with EC while keeping their arms by their sides (EC condition).
3. OL stand on the dominant leg with EO while their arms are crossed over their chest (OL condition).

Crossed-arm positioning was introduced in the one-leg stance to minimize subtle arm movements. This approach has been previously employed in a previous study involving LBP population [17]. Participants were explicitly instructed against using arms for stabilization;

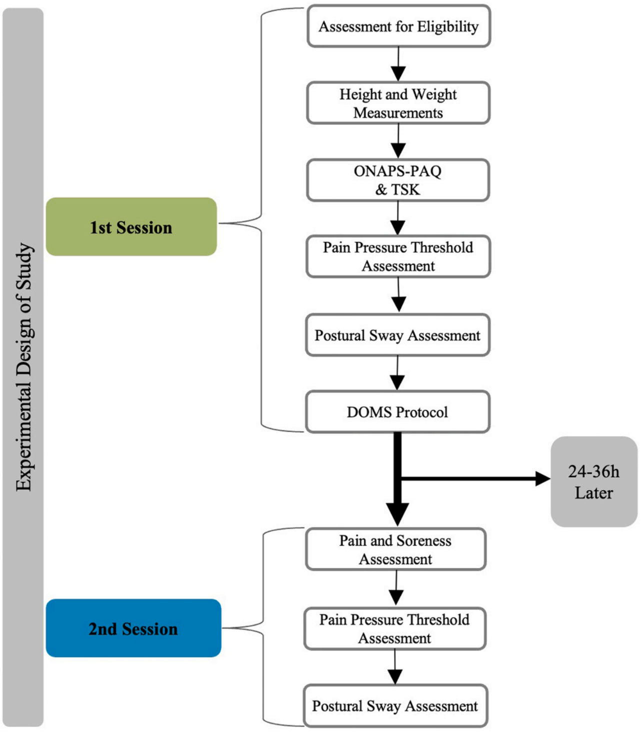

Fig. 1. Flow chart showing the experimental design of the study.

trials with arm use were discarded. In the quiet standing with EO and EC conditions, the distance between the two feet corresponded to shoulder width. In the OL stand condition, the dominant leg was self-reported and determined based on the leg that participants typically use for kicking a ball. The non-dominant leg was raised 10 cm from the force plate and inspected visually throughout the trial. Data from trials, where a loss of balance or a foot displacement occurred, were discarded. In the two EO conditions (quiet standing EO and OL stand condition), participants fixed a target 3 m distant, at eye level. Data acquisition started once the participants felt ready and stable. A series of three trials in each of these conditions was performed, with a 30-second rest between each trial. Each trial lasted 30 s. The order of the conditions was randomized between participants. Individual position of the feet was contoured on a sheet of paper covering the force plate. These contours were used to ensure that the participants returned to the same feet position between trials, conditions, and sessions under the supervision of the experimenters. This protocol has been shown to provide reliable data for balance ability evaluation [18].

2.5. DOMS protocol

Maximal voluntary isometric contractions (MVCs) of the trunk extension were first assessed with participants positioned on the testing apparatus (Fig. 2). In this apparatus, they exerted their MVCs force against a shoulder-attached belt for five seconds. The belt was connected to a force gauge (Model LSB350; Futek Advanced Sensor Technology Inc, Irvine, CA, USA). Participants performed three trials of MVCs with one-minute rest between. After the three trials and a 5-minute rest, participants completed the DOMS protocol and were asked to hold an external load corresponding to 10% of the highest MVCs against their chest with their arms crossed (see Fig. 2 for more details) [6]. The procedure consisted of performing five sets, each comprising 20 repetitions of trunk flexion and extension exercises, with a 1-minute rest period between each set. This resulted in a total of 100 repetitions. Participants received verbal encouragement throughout the entire protocol. In cases where they encountered challenges in completing a full set of 20 repetitions, modifications were applied to both the set size and the rest intervals, ensuring that the overall objective of reaching 100 repetitions was met. All participants successfully accomplished the target of 100 contractions. Additional information about the DOMS protocol can be found in our earlier work [6].

2.6. Pain and soreness rating

At the beginning of the second session, participants were asked to score, on a numeric rating scale (ranging from 0 for no pain/soreness to 10 for maximal pain/soreness), their overall level of perceived pain and soreness in the lower back and legs. Participants reported mean pain rating of 0.83 ± 1.35 for the back and 0.45 ± 0.94 for the legs, as well as mean soreness rating of 4.10 ± 1.55 for the back and 2.65 ± 1.98 for the legs.

2.7. PPT assessment

A hand-held algometer (Model 01163; Lafayette Instrument Company, Lafayette IN, USA) measured PPT in Erector Spinae (L3 level), Gluteus Maximus, Biceps Femoris, and Gastrocnemius on both sides. The right Vastus lateralis served as a control measure for DOMS, expected to be unaffected by eccentric back extension exercises. Participants lay prone on a chiropractic table, and the dynamometer applied a constant force of approximately 1 kg/s [6,19]. PPT assessments, known for consistent between-session reliability [20] were conducted three times per muscle, with participants reporting the transition from pressure to pain [10]. The mean values were calculated for each muscle, and assessment order was randomized between participants, with the same experimenter palpating and conducting assessments.

2.8. Posturographic analysis

Data treatment. Kinetics data from the force plate were collected at sampling frequency of 100 Hz and were low-pass filtered at 10 Hz by a 2nd order Butterworth filter in MATLAB (v.2023a; TheMathWorks, Natick, MA). The anteroposterior (AP) and mediolateral (ML) components of the COP displacement (COP_{AP} and COP_{ML}, respectively) were calculated as follows:

$$COP_{AP} = M_{ML} / F_z$$

$$COP_{ML} = M_{AP} / F_z$$

Where F_z is the vertical ground reaction force applied to the feet; $M_{A/P}$ and $M_{M/L}$ are the moments of force exerted on the surface of the force plate along the AP and ML direction, respectively. COP data were used to calculate the following balance parameters: 95% confidence ellipse area of COP (in mm^2) (Fig. 3. E), COP velocity (in $mm.s^{-1}$), root mean square (RMS) (in mm) (Fig. 3. G), and mean power frequency (MPF) (in Hz) (Fig. 3. H) of COP for both AP and ML directions. These parameters were

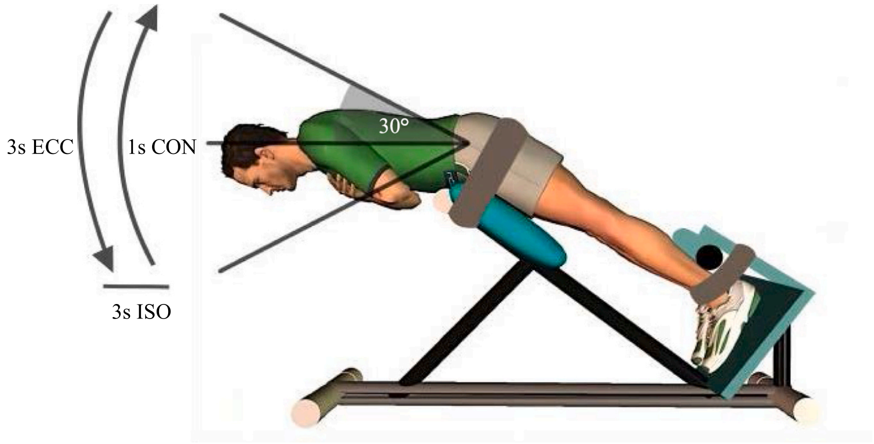

Fig. 2. Illustration of the DOMS Protocol (Abboud et al., 2019). Participants were positioned on a 45° inclined Roman chair with their trunk aligned to the ground. Hip and ankle straps minimizing lower limbs muscle involvement. They executed a 30° trunk flexion over 3 s (eccentric contraction), maintained this position for 3 s (isometric contraction), and returned to the neutral position in 1 s (concentric contraction). Timing was regulated with a metronome (3-3-1). ECC: eccentric contraction; CON: concentric contraction; ISO: isometric contraction.

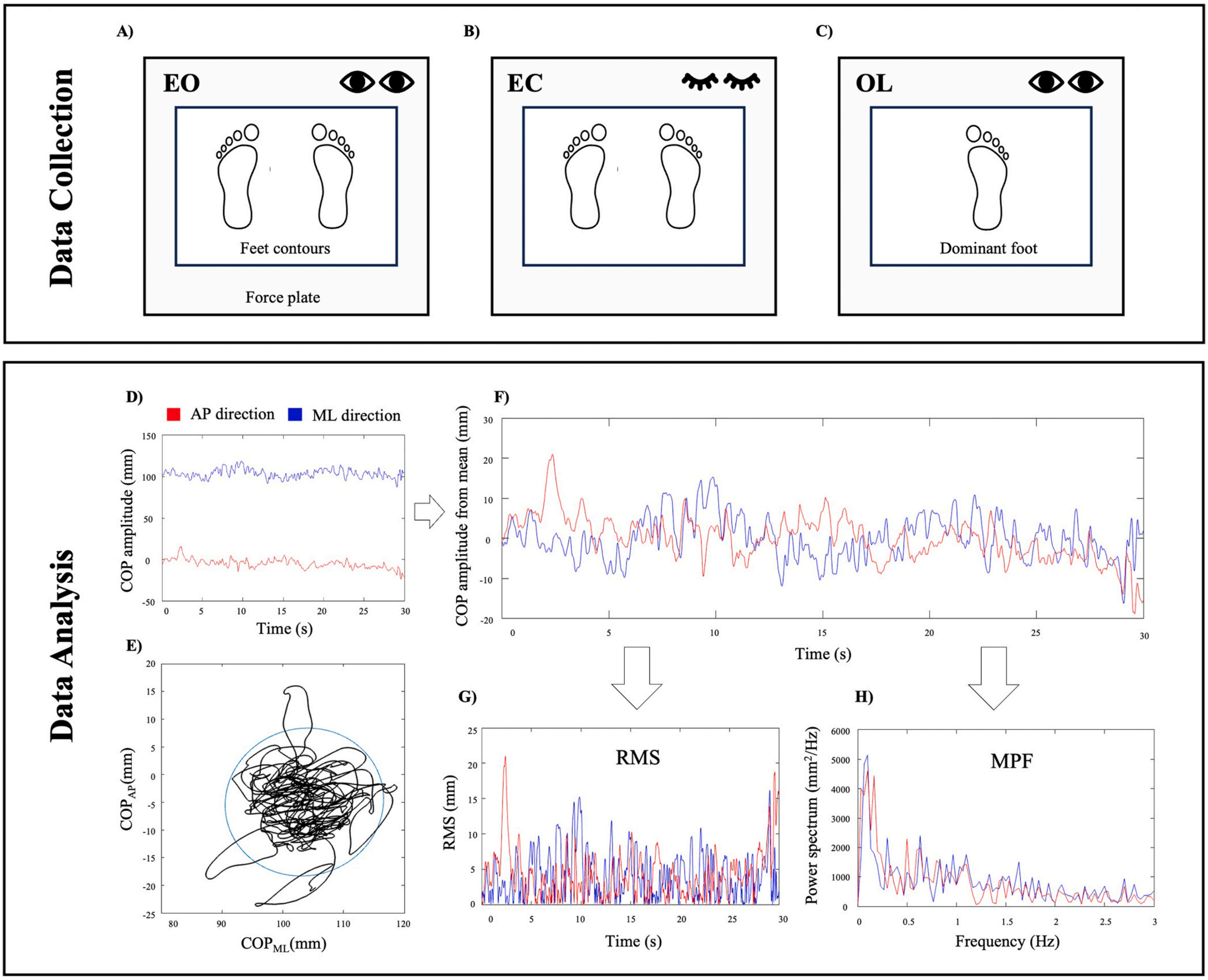

Fig. 3. Data collection and analysis process. On the upper section of the figure are reported three subplots of data collection. The first subplot (A) shows the bipedal condition with eyes opened (EO), the second subplot (B) shows bipedal condition with eyes closed (EO), and the third subplot (C) shows the One-leg stand condition with eyes opened (OL). On the bottom section of the figure, there are five separate data analysis plots of the One-leg condition (n = 1). The initial plot (D) displays the filtered COP data for both the anteroposterior (AP) direction in red and the mediolateral (ML) direction in blue. The second plot (E) illustrates the displacement of the COP area and the ellipse area containing 95% of the COP data points. The third plot (F) represents the oscillations of COP data relative to the mean value. The fourth plot (G) exhibits the root mean square (RMS) of the oscillations used to determine the average RMS value. Finally, the fifth plot (H) shows the fast Fourier transform of the oscillating data, which is used to calculate the mean power frequency (MPF).

calculated over the entire 30 s trials. COP velocity was calculated by dividing sway length by the duration of the recording (30 s) in both the ML and AP axes. The mean COP values along the AP and ML direction was removed from COP data prior to calculating the RMS and the MPF in order to assess the magnitude and frequency of fluctuations normalized by the mean.

2.9. Statistical analysis

Mean values and standard deviations were calculated for each dependent variable described above. Statistical analyses were performed using SPSS Statistics for Mac, version 28 (SPSS Inc., IBM Corp., Armonk, NY, USA). Parametric tests were chosen considering the data's normal distribution, which was evaluated through the Kolmogorov-Smirnov test and visual examination. In cases where the Mauchly test revealed a departure from the assumption of sphericity, the Greenhouse–Geisser correction was used. A within-subject two-way RM ANOVA was conducted to examine the effect of the postural condition (3 levels: EO, EC, OL condition) and the DOMS condition (2 levels: 1st session vs. 2nd session) on the COP variables. Bonferroni post hoc tests were used as needed. The threshold of significance was set at $p < 0.05$. Effect sizes are reported using partial eta-squared (η^2). The effect sizes were classified as small (0.01), medium (0.06), and large ($\geq$ 0.14). Pairwise t-tests were used to assess the differences in PPT values between the 1st session and 2nd session.

3. Results

3.1. Pain sensitivity threshold assessment

Pairwise t-tests showed that PPT was significantly lower in the second session (i.e. under DOMS condition) than in the first session (baseline condition) for the right ($p = 0.003$) and left Erector Spinae muscle ($p = 0.026$), and for the left Biceps Femoris ($p = 0.046$). Details on the PPT scores are reported Table 2.

Table 2
Comparison of pressure-pain threshold (PPT) between the 1st and the 2nd session.

Site	1st session (Kg)	2nd session (Kg)	t (df = 19)	p-value
Right Erector Spinae (L3)	7.54 (3.41)	5.76 (3.78)	3.039	**0.003**
Left Erector Spinae (L3)	7.40 (3.50)	6.02 (3.49)	2.075	**0.026**
Right Gluteus Maximus	6.81 (2.75)	6.57 (2.49)	0.498	0.312
Left Gluteus Maximus	6.32 (2.80)	6.04 (2.60)	0.648	0.262
Right Biceps Femoris	7.52 (2.64)	6.71 (2.58)	1.549	0.069
Left Biceps Femoris	7.32 (3.20)	6.46 (2.88)	1.743	**0.049**
Right Lateral Gastrocnemius	6.92 (3.06)	7.50 (3.25)	-0.854	0.202
Left Lateral Gastrocnemius	5.53 (2.78)	6.72 (2.79)	-0.390	0.350
Right Vastus Lateralis	7.34 (3.28)	7.05 (3.17)	1.057	0.152

*Statistically significant results are highlighted in bold

3.2. *Posturographic analysis*

RM ANOVA showed that there was a significant main effect of the postural condition on all COP variables investigated: COP area ($F_{2,38} = 141.915$, $p < 0.001$, partial $n^2 = 0.882$), COP velocity along the AP ($F_{2,38} = 208.309$, $p < 0.001$, partial $n^2 = 0.916$) and ML direction ($F_{2,38} = 439.016$, $p < 0.001$, partial $n^2 = 0.959$), RMS along the AP ($F_{2,38} = 141.460$, $p < 0.001$, partial $n^2 = 0.882$) and ML ($F_{2,38} = 325.797$, $p < 0.001$, partial $n^2 = 0.945$) direction, and MPF along the AP ($F_{2,38} = 58.421$, $p < 0.001$, partial $n^2 = 0.755$) and ML ($F_{2,38} = 57.049$, $p < 0.001$, partial $n^2 = 0.750$) direction. *Post hoc* tests on the main effect of conditions further revealed that each of these COP variables reached a significantly higher value in the OL stance condition than in both the bipedal EC and EO stance conditions (all with $p < 0.001$). In addition, the COP velocity and the MPF along the AP direction both reached a significantly higher value in the bipedal stance EC condition than in the bipedal stance EO condition ($p < 0.001$). Details of the post hoc test are reported in Fig. 4. In contrast, RM ANOVA showed that there was no significant main effect of DOMS nor significant DOMS X postural condition interaction on any of the COP variables investigated.

4. Discussion

The primary aim of this study was to evaluate the effect of lumbar DOMS on postural stability conditions in healthy participants. Our initial hypothesis was that participants would demonstrate decreased postural stability following the induction of lumbar DOMS with a more pronounced effect during conditions of greater instability. As anticipated this study showed an increase in postural sway when the instability of the condition increases which is consistent with previous work [21]. However, contrary to our initial hypothesis, we did not observe any noticeable effect of DOMS on any COP measures of postural stability in either of the conditions. Thus, participants demonstrated adaptive stability strategies under unstable conditions characterized by an

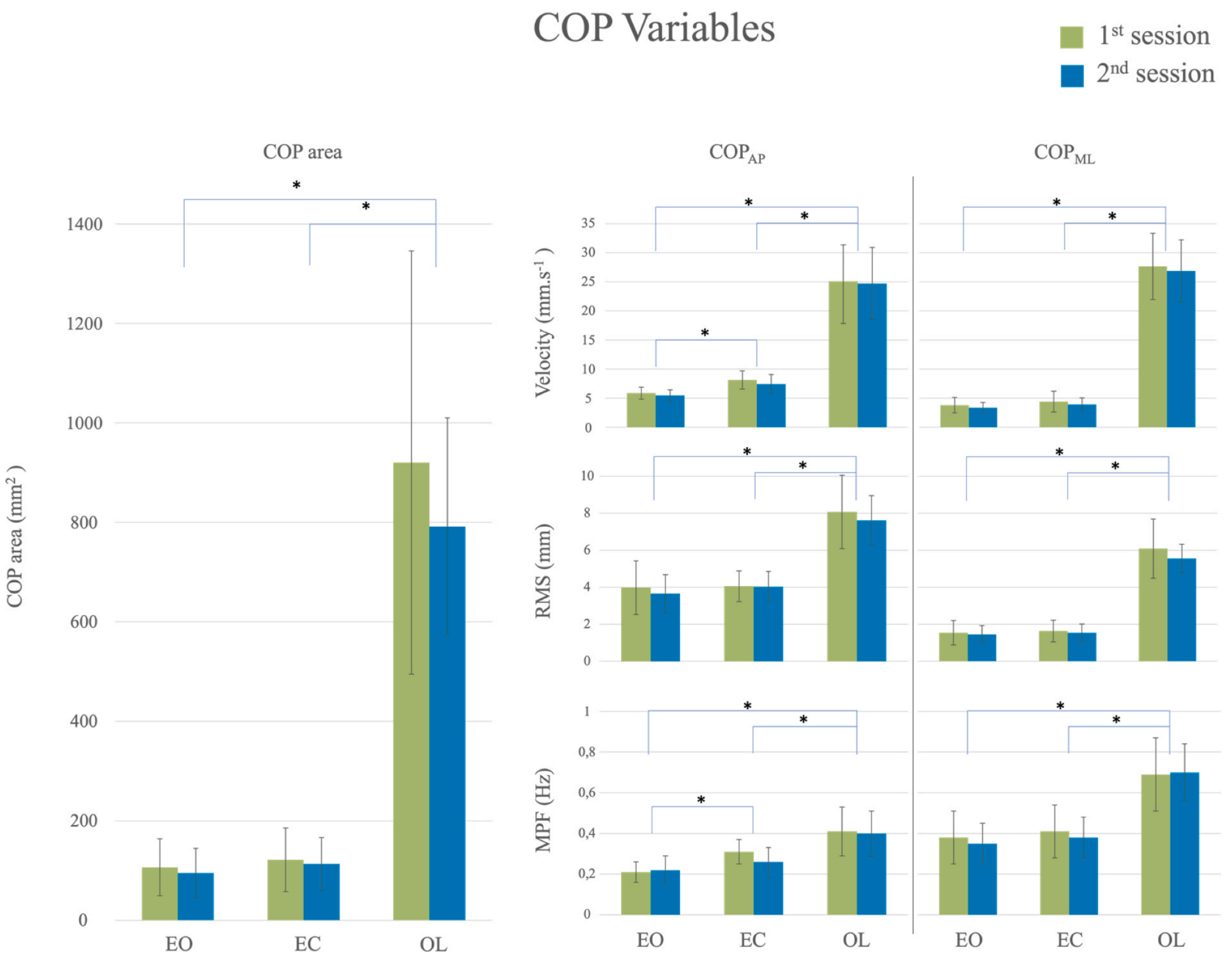

Fig. 4. Impact of the postural conditions and DOMS on the center of pressure (COP) variables. COP Area (mm^2), Velocity (mm.s^{-1}), root mean square (RMS) (mm), mean power frequency (MPF) (Hz) of the COP for both anteroposterior (AP) and mediolateral (ML) direction and both sessions. 1st session in green and 2nd session (with DOMS) in blue. Reported are means and SD (all participants together). EO: quiet standing with eyes opened; EC: quiet standing with eyes closed; OL: One-leg stand condition with eyes opened. * : differences between postural conditions ($P < 0.001$). Note that there was no effect of DOMS on any COP variables.

increase in the COP sway while maintaining balance whether DOMS was present or not.

4.1. Impact of DOMS

The present results showed that the lumbar DOMS protocol yielded mild pain and moderate soreness in the lumbar region, which is partially consistent with previous studies [6,7,10]. Participants in this study reported lower LBP scores compared to other studies using the same protocol [6,7]. Such results may be explained by the high activity levels reported by participants, ranking them as "Active+ ." Regular physical activity and frequent DOMS experiences may have led them to perceive DOMS sensations as less painful. In fact, athletes often have a higher pain tolerance [22] and might possess a greater ability to distinguish between pain and soreness due to their awareness and more frequent exposure to DOMS.

This study found no significant impact of DOMS on parameters such as COP area, velocity, RMS, and MPF along both AP and ML direction. Similar results on postural stability have also been observed with DOMS in other muscles, such as knee flexors and extensors [23,24]. One study observed that DOMS in the knee extensor and flexor muscles led to shifts in movement patterns of the pelvis without modification of COP measures during quiet standing with EO and EC [23]. Similarly, another study inducing hamstring DOMS found no significant modifications in the COP parameters during OL stand condition [24]. The authors suggested that the hip joint multiple degrees of freedom could potentially compensate for any functional deficits caused by hamstring pain [24]. Similar results have been observed with other types of postural perturbation such as induced hypomobility of the lower limb which triggers motor adaptation to maintain stability [25]. DOMS-related disability impact on postural stability may therefore be compensated by the collective contributions of the hip, knee, and ankle joints, especially in unipedal postures. Postural stability during standing can be maintained by two control mechanisms: 1) moving the COP within the base of support (M1), and 2) counter-rotating segments around the center of mass (M2) [26,27]. The present study has only focused on M1 through COP parameters as this mechanism has recently been shown to explain 90% (on average) of the whole-body center of mass acceleration in bipedal postures [26]. However, the contribution of M1 has also been shown to explain only 60% of the center of mass acceleration in more challenging postures, such as unipedal with eyes open, the remaining percentage being explained by M2. It is therefore not excluded that DOMS induced a major change in M2 (e.g. a change in the collective contributions of the hip, knee, and ankle joints) in the more challenging postures. Such change could, however, not be revealed in the present analysis focusing on “classical” COP parameters. Also, it is not excluded that contributions from M1 and M2 changed with DOMS in both the bipedal and unipedal standing conditions. Further analyses of the force plate signals are required to test these hypotheses [27].

4.2. Postural stability changes in lumbar DOMS and chronic LBP

Although the absence of a significant impact of DOMS on postural stability observed in this study is similar to findings from earlier studies involving participants with clinical LBP [28,29], recent findings from a meta-analysis [11] found that individuals with chronic LBP exhibit an increase in postural sway. This includes changes in various parameters, such as COP amplitude, displacement, area, and dispersion, along both the AP and ML directions during quiet standing conditions.

This contrast between our findings and the meta-analysis results could potentially be attributed to variations in how proprioception is modulated by chronic pain versus acute DOMS. The decrease in proprioception associated with DOMS [5,7] is believed to result solely from the nociceptive input [5,23], leading to decreased motor cortex excitability [30] resulting in a reduction of motor output, thereby negatively affecting proprioception [5]. Conversely, the decrease in proprioception in chronic LBP is believed to originate from numerous factors. These factors include muscle fatigue [31], which can be attributed to the decrease in muscle quality observed in individuals with LBP [32]. Additionally, the intensity of pain [33], and psychological factors such as movement-related fear [34] and functional disability [35] can also contribute to this reduction in proprioception.

Moreover, the disparity in pain intensity between the meta-analysis and our study may also contribute to this difference. Subgroup analysis conducted within the meta-analysis found more pronounced effect sizes when perceived pain intensity was higher than the median value (4.73/10) across all studies included [11]. Hence, the low level of pain in this study (0.83/10 ± 1.35) could explain these different findings. Indeed, pain can impact the function and transmission of mechanoreceptors [36] as well as the central modulation of proprioceptive spindles in muscles [37]. These disruptions in proprioceptive information hamper the accuracy of sensory integration processes, prolonged latency by reducing muscle spindle feedback, and reduced ability for real-time corrections [38], which could result in compensatory shifts in the COP. The magnitude of these disturbances is likely influenced by the intensity of pain, as demonstrated by research that has shown that greater pain intensity induces higher postural sway velocity in both AP and ML directions, as well as an increased sway area of the COP [33].

4.3. Limitation

This study has limitations. Lumbar DOMS protocol triggers DOMS not only in the lumbar region but also in the entire posterior chain, including the lower limb muscles which could have influenced the results. Nevertheless, this factor was controlled by measuring the PPT in the leg regions and inquiring about sensations of pain and soreness.

Moreover, it is possible that participants employed local adaptive strategies, such as using hip, trunk, or ankle adjustments to preserve stability in both unstable balance conditions and under DOMS influence. The contribution of such local strategies requires further analysis of the force plate signals [27]. Additionally, results must be interpreted with caution, as their applicability might be more relevant to a younger population, given our specific age group.

5. Conclusion

In conclusion, this study investigated the impact of lumbar DOMS on postural stability in healthy individuals and the relevance of DOMS as a pain model for clinical LBP. The results revealed no impact of lumbar DOMS on COP measures of postural stability. Although DOMS induces similar trunk sensorimotor adaptations to clinical LBP, it does not appear to trigger similar postural stability adaptations.

CRediT authorship contribution statement

Descarreaux Martin: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Yiou Éric:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Abboud Jacques:** Conceptualization, Formal analysis, Investigation, Supervision, Validation, Writing – review & editing. **Schwendenmann Yves:** Conceptualization, Investigation, Methodology, Resources, Writing – review & editing. **Houle Mariève:** Conceptualization, Investigation, Methodology, Resources, Writing – review & editing. **Memari Sahel:** Conceptualization, Investigation, Methodology, Resources, Writing – review & editing. **Ducas Julien:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] K. Cheung, P.A. Hume, L. Maxwell, Delayed onset muscle soreness, Sports Med. (2003) 145–164.

[2] L.F. Farias-Junior, R.A.V. Browne, Y.A. Freire, F.F. Oliveira-Dantas, T.M.A. M. Lemos, N.L. Galvão-Coelho, et al., Psychological responses, muscle damage, inflammation, and delayed onset muscle soreness to high-intensity interval and moderate-intensity continuous exercise in overweight men, Physiol. Behav. 199 (2019) 200–209.

[3] N.S. Weerakkody, N.P. Whitehead, B.J. Canny, J.E. Gregory, U. Proske, Large-fiber mechanoreceptors contribute to muscle soreness after eccentric exercise, J. Pain. 2 (4) (2001) 209–219, https://www.jpain.org/article/S1526-5900(01)83309-5/fulltext https://www.jpain.org/article/S1526-5900(01)83309-5/pdf.

[4] J.-M. Coudreuse, P. Dupont, C. Nicol, Douleurs musculaires post-effort, J. De. Traumatol. du Sport 24 (2) (2007) 103–110.

[5] U. Proske, N.S. Weerakkody, P. Percival, D.L. Morgan, J.E. Gregory, B.J. Canny, Force-matching errors after eccentric exercise attributed to muscle soreness, in: Clinical and Experimental Pharmacology and Physiology, 30, 2003, pp. 576–579, https://onlinelibrary.wiley.com/doi/abs/10.1046/j.1440-1681.2003.03880.x?sid=nlm%3Apubmed.

[6] J. Abboud, A. Lessard, M. Piché, M. Descarreaux, Paraspinal muscle function and pain sensitivity following exercise-induced delayed-onset muscle soreness, Eur. J. Appl. Physiol. 119 (2019) 1305–1311, https://link.springer.com/content/pdf/10.1007/s00421-019-04117-6.pdf.

[7] M. Houle, C. Daneau, A. Lessard, M.-A. Mercier, M. Descarreaux, J. Abboud, Short-term effect of delayed-onset muscle soreness on trunk proprioception during force reproduction tasks in a healthy adult population: a crossover study, Eur. J. Appl. Physiol. 120 (2020) 181–190, https://link.springer.com/content/pdf/10.1007/s00421-019-04262-y.pdf.

[8] A.-K.R. Osthoff, M.J. Ernst, F.M. Rast, D. Mauz, E.S. Graf, J. Kool, C.M. Bauer, Measuring lumbar reposition accuracy in patients with unspecific low back pain: systematic review and meta-analysis, Spine 40 (2) (2015) E97–E111.

[9] M.H. Tong, S.J. Mousavi, H. Kiers, P. Ferreira, K. Refshauge, J. van Dieën, Is there a relationship between lumbar proprioception and low back pain? A systematic review with meta-analysis, Arch. Phys. Med. Rehabil. 98 (1) (2017) 120–136, https://www.archives-pmr.org/article/S0003-9993(16)30245-3/fulltext.

[10] M.D. Bishop, M.E. Horn, S.Z. George, M.E. Robinson, Self-reported pain and disability outcomes from an endogenous model of muscular back pain, BMC Musculoskelet. Disord. 12 (1) (2011) 1–10.

[11] J. Park, V.Q. Nguyen, R.L. Ho, S.A. Coombes, The effect of chronic low back pain on postural control during quiet standing: a meta-analysis, Sci. Rep. 13 (1) (2023) 7928, https://www.nature.com/articles/s41598-023-34692-w.pdf.

[12] R.A. da Silva, E.R. Vieira, K.B. Fernandes, R.A. Andraus, M.R. Oliveira, L. A. Sturion, M.G. Calderon, People with chronic low back pain have poorer balance than controls in challenging tasks, Disabil. Rehabil. 40 (11) (2018) 1294–1300.

[13] V. Korakakis, K. O'Sullivan, A. Kotsifaki, Y. Sotiralis, G. Giakas, Lumbo-pelvic proprioception in sitting is impaired in subgroups of low back pain–But the clinical utility of the differences is unclear. A systematic review and meta-analysis, Plos One 16 (4) (2021) e0250673 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8075231/pdf/pone.0250673.pdf.

[14] J. Allum, B. Bloem, M. Carpenter, M. Hulliger, M. Hadders-Algra, Proprioceptive control of posture: a review of new concepts, Gait Posture 8 (3) (1998) 214–242.

[15] M. Charles, D. Thivel, J. Verney, L. Isacco, P. Husu, H. Vähä-Ypyä, et al., Reliability and validity of the ONAPS physical activity questionnaire in assessing physical activity and sedentary behavior in French adults, Int. J. Environ. Res. Public Health 18 (11) (2021) 5643, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8197457/pdf/ijerph-18-05643.pdf.

[16] D.J. French, C.R. France, F. Vigneau, J.A. French, R.T. Evans, Fear of movement/(re) injury in chronic pain: a psychometric assessment of the original English version of the Tampa scale for kinesiophobia (TSK), Pain 127 (1-2) (2007) 42–51.

[17] T. Maribo, K. Stengaard-Pedersen, L.D. Jensen, N.T. Andersen, B. Schiøttz-Christensen, Postural balance in low back pain patients: intra-session reliability of center of pressure on a portable force platform and of the one leg stand test, Gait Posture 34 (2) (2011) 213–217.

[18] R.A. Da Silva, M. Bilodeau, R.B. Parreira, D.C. Teixeira, C.F. Amorim, Age-related differences in time-limit performance and force platform-based balance measures during one-leg stance, J. Electromyogr. Kinesiol. 23 (3) (2013) 634–639.

[19] L.S. Chesterton, J. Sim, C.C. Wright, N.E. Foster, Interrater reliability of algometry in measuring pressure pain thresholds in healthy humans, using multiple raters, Clin. J. Pain. 23 (9) (2007) 760–766.

[20] L. Potter, C. McCarthy, J. Oldham, Algometer reliability in measuring pain pressure threshold over normal spinal muscles to allow quantification of anti-nociceptive treatment effects, Int. J. Osteopath. Med. 9 (4) (2006) 113–119.

[21] K.M. Guskiewicz, D.H. Perrin, Research and clinical applications of assessing balance, J. Sport Rehabil. 5 (1) (1996) 45–63.

[22] J. Tesarz, A.K. Schuster, M. Hartmann, A. Gerhardt, W. Eich, Pain perception in athletes compared to normally active controls: a systematic review with meta-analysis, Pain 153 (6) (2012) 1253–1262.

[23] P. Iodice, P. Ripari, G. Pezzulo, Local high-frequency vibration therapy following eccentric exercises reduces muscle soreness perception and posture alterations in elite athletes, Eur. J. Appl. Physiol. 119 (2019) 539–549, https://link.springer.com/content/pdf/10.1007/s00421-018-4026-5.pdf.

[24] N. Sarabon, A. Panjan, J. Rosker, B. Fonda, Functional and neuromuscular changes in the hamstrings after drop jumps and leg curls, J. Sports Sci. Med. 12 (3) (2013) 431.

[25] A. Delafontaine, P. Fourcade, J. Honeine, S. Ditcharles, E. Yiou, Postural adaptations to unilateral knee joint hypomobility induced by orthosis wear during gait initiation, Sci. Rep. 8 (1) (2018) 830.

[26] R. Tisserand, J. Plard, T. Robert, Relative contributions of postural balance mechanisms reveal studying the CoP displacement alone may be incomplete for analysis of challenging standing postures, Gait Posture 101 (2023) 134–137.

[27] A.L. Hof, The equations of motion for a standing human reveal three mechanisms for balance, J. Biomech. 40 (2) (2007) 451–457.

[28] K. Claeys, S. Brumagne, W. Dankaerts, H. Kiers, L. Janssens, Decreased variability in postural control strategies in young people with non-specific low back pain is associated with altered proprioceptive reweighting, Eur. J. Appl. Physiol. 111 (2011) 115–123, https://link.springer.com/content/pdf/10.1007/s00421-010-1637-x.pdf.

[29] L. Shigaki, E.R. Vieira, A.W. de Oliveira Gil, C.G.A. Araújo, M.Z. Carmargo, L. A. Sturion, et al., Effects of holding an external load on the standing balance of older and younger adults with and without chronic low back pain, J. Manip. Physiol. Ther. 40 (4) (2017) 284–292, https://www.jmptonline.org/article/S0161-4754(17)30020-9/fulltext.

[30] A. Rohel, J. Bouffard, P. Patricio, N. Mavromatis, M. Billot, J.S. Roy, et al., The effect of experimental pain on the excitability of the corticospinal tract in humans: A systematic review and meta-analysis, Eur. J. Pain. 25 (6) (2021) 1209–1226.

[31] S. Taimela, M. Kankaanpää, S. Luoto, The effect of lumbar fatigue on the ability to sense a change in lumbar position: a controlled study, Spine 24 (13) (1999) 1322.

[32] T. Matheve, P. Hodges, L. Danneels, The role of back muscle dysfunctions in chronic low back pain: state-of-the-art and clinical implications, J. Clin. Med. 12 (17) (2023) 5510.

[33] A. Ruhe, R. Fejer, B. Walker, Is there a relationship between pain intensity and postural sway in patients with non-specific low back pain? BMC Musculoskelet. Disord. 12 (1) (2011) 1–8.

[34] A. Meinke, C. Maschio, M.L. Meier, W. Karlen, J. Swanenburg, The association of fear of movement and postural sway in people with low back pain, Front. Psychol. 13 (2022) 1006034 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9716132/pdf/fpsyg-13-1006034.pdf.

[35] S. Van Wesemael, K. Bogaerts, L.D. Baets, N. Goossens, E. Vlemincx, C. Amerijckx, et al., The association between pain-related psychological variables and postural control in low back pain: a systematic review and meta-analysis, Gait Posture (2023) https://www.sciencedirect.com/science/article/pii/S0966636223014698.

[36] H. Torebjörk, L. Lundberg, R. LaMotte, Central changes in processing of mechanoreceptive input in capsaicin-induced secondary hyperalgesia in humans, J. Physiol. 448 (1) (1992) 765–780.

[37] N.F. Capra, J.Y. Ro, Experimental muscle pain produces central modulation of proprioceptive signals arising from jaw muscle spindles, Pain 86 (1-2) (2000) 151–162.

[38] S.S. Kantak, T. Johnson, R. Zarzycki, Linking pain and motor control: conceptualization of movement deficits in patients with painful conditions, Phys. Ther. 102 (4) (2022) pzab289.